DAMS FROM THE BEGINNING

By

Robert B. Jansen [1]

Introduction

The engineering of dams is a vital part of the story of civilization. Reservoirs for water supply were undoubtedly among the earliest structures devised by mankind. The role that dams have played over the ages is documented in many records of ancient lands. Dams have been linked closely to the rise and decline of civilizations, especially to those cultures highly dependent upon irrigation.

Dams have served people for at least 5,000 years, as evidenced in the cradles of civilization, in Babylonia, Egypt, India, Persia, and the Far East. The remains of these ancient structures exist in both the old and the new worlds, marking the attainments of societies which have long since died. Many of the outstanding waterworks of antiquity eventually declined into disuse because the knowledge of their designers and builders was not preserved by the generations who inherited them. And without water the civilizations which it had supported faded away. .

History does not record exactly when irrigation systems and dams were first constructed. Study of ancient China, India, Iran, and Egypt does reveal that such work in these lands was begun thousands of years ago, and provided lifelines on which their civilizations depended. Menes, the first Pharaoh of Egypt, ordered irrigation works to draw from the River Nile. In China, construction of impressive dams was accomplished on the Min River for flood control and diversion of water to nearby farm lands. The sacred books of India cite the very early operation of dams, channels, and wells; evidence that this land may have been the birthplace of the art. The Persians of ancient times recognized the importance of irrigation to the sustenance of civilization. By excavating underground water tunnel and gallery systems (quanats) and by constructing many dams, they accomplished projects which rank among the greatest in history. In the ruins at Sialak, near Kashan, are to be seen traces of irrigation channels which are considered to be as much as 6,000 years old, suggesting that irrigation was practiced there from very early times, even before the arrival of the Aryans in the land now known as Iran.

The Period B.C.

The remote history of dams is not well known. Most dates of events earlier than 1000 B.C. can be only estimated. This is particularly true of early Egypt, whose peculiar chronology sometimes sheds only dim light on the many dynasties and their engineering achievements.

Ruins of ancient works in India and Sri Lanka (Ceylon) offer some evidence of how water reservoirs were created by early peoples. A common method of construction involved the placement of earth barriers across streams. Some of the lakes formed were of vast area. The materials for the embankment were transported in baskets or other containers. Compaction was accomplished incidentally by the trampling feet of the carriers. Even today in some countries where labor costs are relatively low, this procedure is still used.

Turning to the most available materials, the ancient dam builders made liberal use of soils and gravels. Since they had only the slightest understanding of the mechanics of materials or of flood flows, their methods were haphazard, and their works often failed. Embankment dams were low on the scale of public confidence for many centuries.

One of the earliest accounts of any major engineering work relates to the founding of Memphis on the River Nile **(fig. 1-1)**, which can only be estimated at sometime between 5,700 B.C. and 2,700 B.C. The historian Herodotus attributed this construction to Menes, the first king of the initial Egyptian dynasty. According to some interpretations of the accounts of Herodotus, King Menes had a masonry dam constructed on the Nile at Kosheish, about 20 kilometers (12 miles) upstream from the site of his planned capital at Memphis.

This version, considered by some historians to be no more than legend, says that before founding the capital, Menes altered the course of the Nile to the east side of the valley rather than the west. One of his purposes re-

[1] Source – Dams and Public Safety (Part I) by Robert B. Jansen, U.S. Department of the Interior, Bureau of Reclamation (1980). The U.S. Society on Dams expresses its appreciation to the author, Mr. Jansen and the Bureau of Reclamation for allowing the use of the historical information from the publication “Dams and Public Safety”. This is an important contribution to understanding the importance of dams to society and our every day lives.

portedly was to assure enough space for the city west of the river. The location provided a better defense perimeter on the east, whence

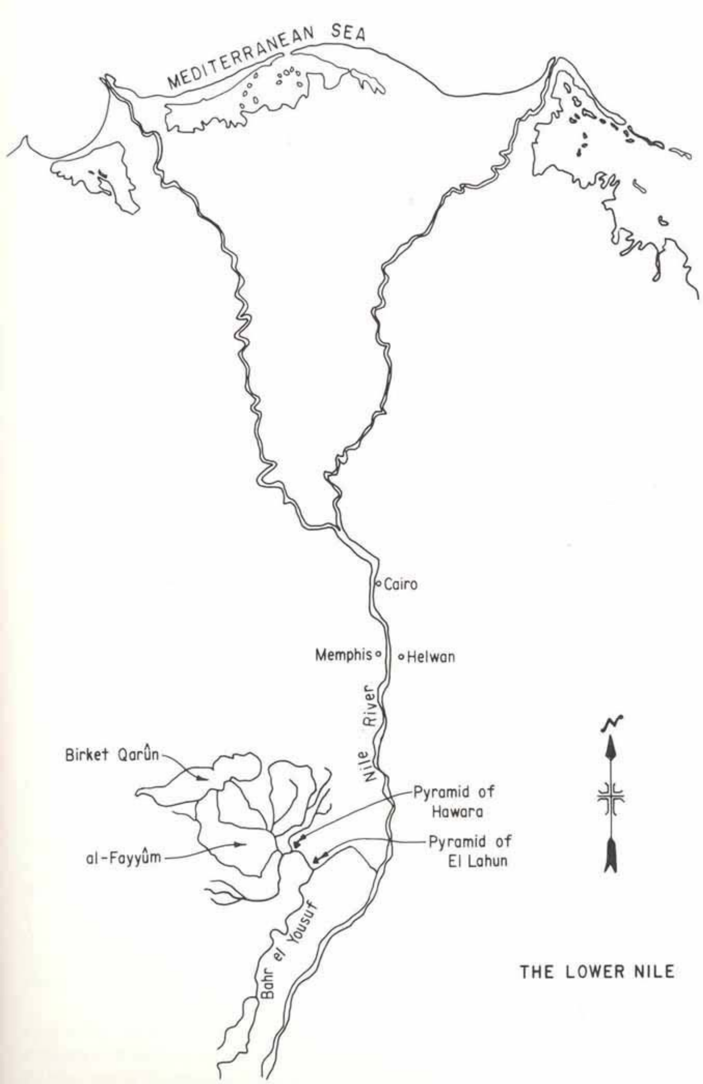


Figure 1-1.—The Lower Nile. P-801-D-79287.

his enemies usually approached. To accomplish this, he is reported to have constructed an immense dam across the river near the Libyan Hills, diverting the stream to a new channel.

Some translations of the writings of Herodotus suggest that the dam was composed of cut-stone masonry. It is reported to have reached a height of about 15 meters (50 feet) and a crest length of 450 meters (1475 feet). The skepticism of modern historical analysts toward this account stems from the magnitude of the project, which they judge to have been beyond the capability of builders of that time.

Elsewhere in Egypt, well-preserved remains of other masonry barriers can still be seen. The abutments of what some archeologists regard as one of the oldest dams in the world still survive in the normally dry channel of the Wadi el-Garawi near Helwan, about 32 kilometers (20 miles) south of Cairo. At some time - perhaps as early as the reign of Khufu (King of Egypt about 2900-2877 B.C.) - the Sadd el-Kafara Dam was built in the wadi to impound water for workmen in the nearby quarries.

The dam had a crest length of about 107 meters (350 feet). Its height was 11 meters (37 feet). The faces were formed by rubble-masonry walls, each 24 meters (78 feet) thick at the base and extending to the top of the dam. The total volume of these two rock walls was about 22,900 cubic meters (30,000 cubic yards). At the base, the walls are separated by a distance of 36 meters (118 feet). Evidently the dam did not have the benefit of a cutoff trench excavated in the foundation. The core was filled with approximately 54,400 metric tons (60,000 tons) of gravel and other stones and probably some earth. The exposed face of the upstream wall was lined with stepped rows of roughly cut limestone blocks, evidently set with un-mortared joints. The stones, reportedly having an average weight of approximately 23 kilograms (50 pounds), were placed in steps about 0.3 meter (1 foot) high on a slope of 3 vertical on 4 horizontal. The massive section had a thickness from face to face of 84 meters (274 feet) at the base and nearly 61 meters (200 feet) at the crest. There is evidence that the top of the dam sloped longitudinally toward the center, causing overflow to be concentrated at that point.

The major deficiency in this dam apparently was its lack of a spillway. This was a serious omission, since the Nile watershed is subject to cloudbursts that cause damaging floods in the tributary wadis. The reservoir capacity of only about 570,000 cubic meters (460 acre-feet) was insufficient to provide significant flood detention. Evidently, the dam was overtopped and its central section was broken away soon after completion of construction, since there is no sign of siltation in the reservoir.

Although its builders may have expected the lower crest elevation at the middle to serve as a spillway, the core at that point was inadequately protected from erosion by overtopping waters. This primary mistake was made at many dams in other areas in later history. The Sadd el-Kafara failure probably discouraged the early Egyptians from constructing other dams of the same composite section.

One of the outstanding reclamation projects in history was created by the Theban Dynasty of 2000 to 1788 B.C., which converted the great desert basin of al-Fayyum into fertile farmland west of the lower Nile. In the valley of the Nile, less than 90 kilometers (56 miles) upstream from Memphis, there is a gap in the Libyan Hills leading to this immense depression, whose bottom is much lower than the Nile. The basin, roughly 80 kilometers (50 miles) in length and 48 kilometers (30 miles) in width, now contains a lake called the Birket Qarun. A narrow, rocky gorge connects the depression with the west branch of the Nile known as Bahr el Yousuf (Canal of Joseph). In ancient times, there may have been a natural overflow into al-Fayyum from the Nile when the river was passing extreme floods. Some scholars believe that the Theban kings enlarged and controlled this channel to divert the waters for land reclamation.

Dams also were constructed across ravines leading into the basin, apparently to capture the runoff during the wet season. One of these dams was a barrier across the Wadi Gezzaweh, a ravine about 73 meters (240 feet) wide at the site. The dam was 44 meters (143 feet) wide at the base and had a height of approximately 11 meters (36 feet). It had a composite embankment consisting of a lower zone of irregular stones embedded in clay, an intermediate rockfill zone of undressed limestone blocks, and an upper section composed of cut stones laid in steps.

Many of the ancient dams such as this did not have separate spillways. During overflow the stepped courses of stone on the slope tended to dissipate the energy of the falling water and to protect the structure from scour. Eventually, the middle of the barrier across the Wadi Gezzaweh was broken loose by a flood. Remnants of the dam can still be seen at the abutments.

The monarch credited with the plan for diverting part of the Nile flow into the enormous al-Fayyum was Amenemhat of the 12th dynasty. The Greeks call him Moeris. According to some reports, Amenemhat could see the potential of this depression as a reservoir for the surplus floodwaters, and he had a channel dug which provided conveyance from the Bahr el Yousuf. Although a connection is believed to have existed between the river and the basin as far back as the reign of King Menes of the first dynasty, Amenemhat reportedly widened and deepened the canal, thus facilitating diversion of the excess floodwaters of the river. This may have been not long after 2000 B.C.

Herodotus gave a first account of the lake in about 430 B.C., saying "Now the Labyrinth being such as I have described, the lake named that of Moeris causes still greater astonishment, on the bank of which the Labyrinth was built.

"The water in the lake is not derived from local sources, for the earth in that part is exceedingly dry and waterless, but it is brought in from the Nile by a canal. It takes six months filling and six months flowing back ***."

Strabo, writing in 20 B.C., added: "It has also a remarkable lake, called the lake of Moeris, large enough to be called a sea, and resembling the open sea in color.

"Thus the lake of Moeris is from its size and depth capable of receiving the overflow of the Nile at its rising, and preventing the flooding of houses and gardens; when the river falls, the lake again discharges the water by a canal at both mouths, and it is available for irrigation. There are regulators at both ends for controlling the inflow and outflow."

Recent scholars have questioned these accounts of the system's operation, suggesting that the diverted waters more likely were applied directly to irrigation of the slopes of the depression, before reaching storage. Investigators have not all agreed in their estimates of the size of the lake. Some have believed that only the lower levels of al-Fayyum impounded water. Others contend that the whole depression was inundated except for a few high points, and that the depth of the lake may have been as great as 91 meters (300 feet).

According to Sir William Willcocks, who studied the area painstakingly, "Lake Moeris *** had a surface of 1,700 million of square meters, a capacity of some 50,000 million cubic meters, and, being drained back into the Nile and kept at a low level, it was able to take from a flood 13,000 million cubic meters of water, and 3000 million of cubic meters extra for every year it was not used. It was capable of reducing a very high flood to one of moderate dimensions; and, if injudiciously or maliciously opened in an ordinary flood, it was capable of depriving a great part of Lower Egypt of any basin irrigation at all, for such irrigation utilized only the surface waters of the Nile flood."

The Bahr el Yousuf carried the floodwaters which were diverted. It was part of a complex system of natural channels, canals, and dams. The connecting canal has been reported to have been 13 kilometers (8 miles) long, 49 meters (160 feet) wide, and 9 meters (30 feet) deep. The dams in the project were constructed using both earth and masonry, and the flow of the water was controlled by gates.

The Ha-Uar of the Hyksos (1788-1580 B.C.), now called Hawara, is where the pyramid of the Labyrinth stands and where the Labyrinth and regulating dams diverted the Nile's waters. The main regulators were two earth dams 10 kilometers (6 miles) apart, closing the gap between the river and the lake. In that era, the Nile evidently flowed in two channels opposite the intake of the canal. The Bahr el Yousuf of the 20th century at Lahoun was in those times either the main channel of the Nile as it was in King Menes' day or of such large capacity that the cutting of the two dams at Hawara Eglan and Hawara el Makta diverted a large part of the Nile's flow.

Much of Egypt in those days was under basin irrigation and depended for its life on the river being held high enough to be diverted into the distribution systems. When the Nile was dangerously high, flood flows were diverted through the canal into Lake Moeris. If the barriers were breached during lower river flows, the Nile in Lower Egypt could be lowered so drastically that a famine could ensue. Egyptian history tells of four famines of long duration. One was the famine of Joseph's time, about *1730* B.C. There were two kingdoms then in Egypt, the Hyksos of Lower Egypt and the Egyptians of Upper Egypt. The frontier was at the canal into Lake Moeris. By capturing Lower Egypt's frontier fort and breaching the dams controlling discharge into the depression, the King of Upper Egypt reportedly produced Joseph's famine. Retaking of the fort and restoration of the barriers brought the drought to an end.

The decline of Lake Moeris 1500 years after Joseph's time has been attributed to the gradual diminution of the Lahoun branch of the Nile due to the less frequent use of the wasteway as the irrigation systems in lower Egypt were established. Eventually, the branch became so small that the diversion had little effect on the Nile.

In Babylonia and Assyria, irrigation was extensively developed in the Tigris and Euphrates Valleys **(fig. 1-2)** as early as 2100 B.C. This reached its peak much later in Sassanian times. On the Tigris River, two great canals diverted from the final rapids near Beled. These were the Nahrwan Canal, extending for 250 kilometers (155 miles) on the left bank and an equally wide but shorter canal on the right bank, known as the Dijail Canal.

Traces of the Nahrwan Canal, which was estimated to be as much as 122 meters *(400* feet) wide and 5 meters (15 feet) deep, can still be identified. To facilitate de-silting, the canal had two intakes, each with sufficient capacity to serve the system while the other was shut down for maintenance. The upper intake diverted water from the Tigris at Dura, and the lower one joined the canal about 60 kilometers (37 miles) downstream at Kudesieh, where there were large regulators.

At some time during the operation of the Nahrwan Canal, its diversion from the Tigris River may have been accomplished by an earth dam. However, the ruins found at the river near the ancient headworks are of massive rubble masonry. Stoneworks were also used to divert tributary streams such as the Atheim (also called Adheim or Adhaim) into the Nahrwan Canal. Parts of the Atheim Dam were still in evidence at the beginning of the 20th century. The Atheim River goes through the Hamrin hills about 80 kilometers (50 miles) from the Tigris. Evidently a masonry dam 17 meters (56 feet) high was erected on the river in this vicinity for diversion into two canals, the Nahr Rathan and the Nahr Batt. These served water on both sides of the Atheim. The Nahr Batt joined the Nahrwan Canal at a regulator made of masonry.

Another notable old dam was the Marduk Dam on the Tigris River north of Baghdad and south of Samarra. It survived the Assyrian, Chaldean, Persian, Greek, Roman, and Sassanian dominations; but it breached and was left in ruin in the 13th century A.D. This dam was constructed of materials including "reeds," according to the inscription on a clay tablet dating from roughly 2000 B.C. The barrier got its name from the Babylonian Marduk, whose history is closely tied to the biblical Nimrod. Tradition holds that Nimrod, the reputed builder of the city of Nineveh, put a large earthfill across the Tigris and thus elevated its level about 12 meters (40 feet) to create a major diversion.

The dam across the ancient bed of the Tigris above Opis is still known as Marduk Dam. The "reeds" referred to on the clay tablet were probably timbers placed as a kind of cofferdam to protect the embankment during construction. These wood members may have been left in the fill in the hope that they would provide some resistance to erosion.

Some observers believe that Nimrod also may have built diversion works farther upstream on the Tigris to supply a large canal along the edge of the valley above the city of Mosul, across the river from the site of Nineveh. Remnants of these works can still be seen.

One of the most impressive ancient water systems was developed in Judah by King Solomon (1018-978 B.C.). Some of these facilities have been rehabilitated and have provided service to Jerusalem as they did many centuries ago. The water source is in the hills southwest of the city. Solomon's system included a series of three reservoirs constructed in a valley among those hills. The basins were shaped with essentially straight boundaries, each having four sides, with the lowest reservoir additionally divided into two chambers by a transverse wall. Dimensions of the ponds vary from about 110 meters (360 feet) to 146 meters (480 feet) in length and from approximately 8 meters (27 feet) to 19 meters (63 feet) in depth. Part of the water supply came from springs at the reservoirs. One of these fed a tank at the side of the uppermost impoundment, where flow was controlled so that delivery could be made either into storage or into the aqueduct extending to Jerusalem.

The southern corner of Arabia, where the Red Sea meets the Gulf of Aden, embraces a land famed for its fertility. This region, known today as Yemen, was occupied in ancient times by several kingdoms, including Saba (Sheba) and Qataban. Records on stone slabs, plaques, and monuments attest to the high level of engineering attained in the area.

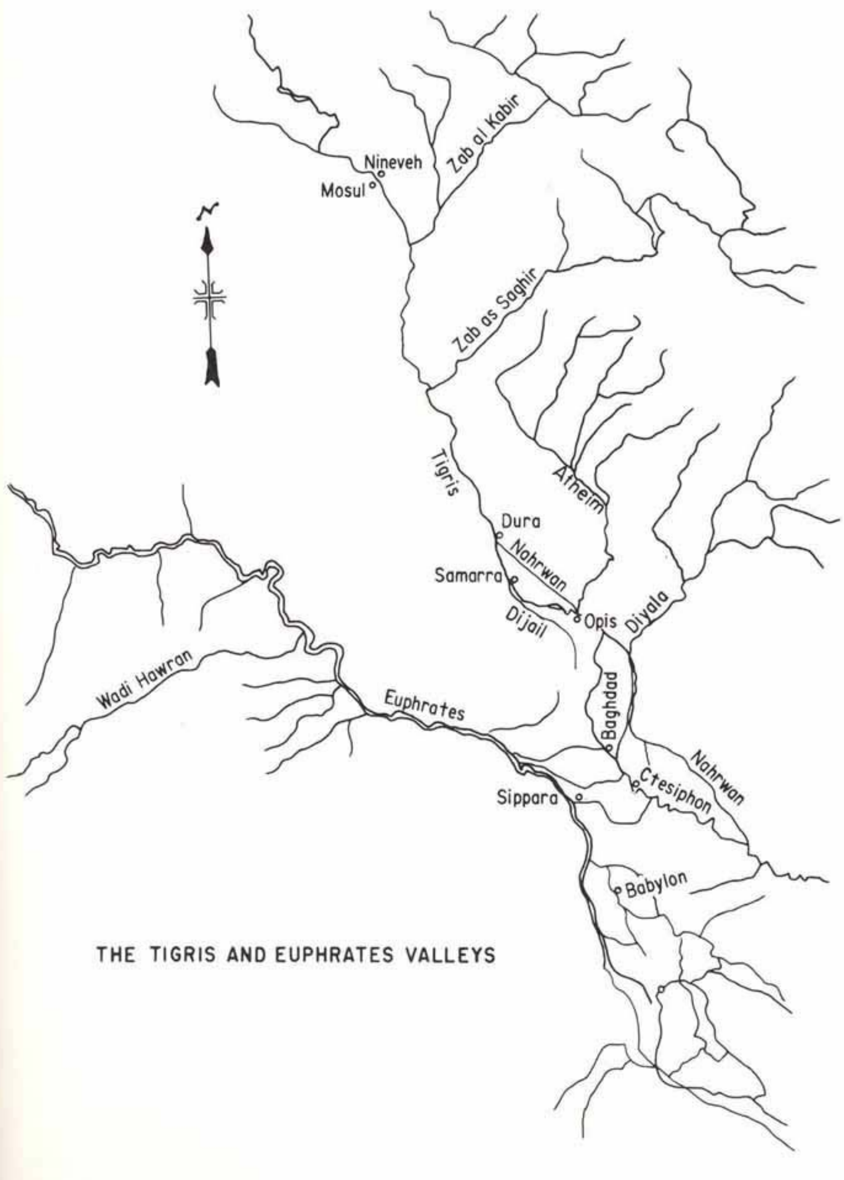


Figure 1-2.—The Tigris and Euphrates River Valleys. P-801-D-79288.

Irrigation systems of impressive detail and extent were developed by the South Arabian people. Their lands supported a thriving agriculture for at least 2,000 years. The Sabaeans, or people of Sheba, were concentrated mostly around Marib, the hub of an important network of water supply.

Marib may have been the capital governed by the Queen of Sheba in about 950 B.c. This city was probably considerably older than the Qatabanian cities in Beihan. There appears to be little doubt that it was founded in the second millennium B.C. and was occupied continuously until the seventh century A.D. The flourishing economy in the city and its environs was made possible by large dams which impounded the runoff from the hills and provided soil conservation and irrigation. Such structures existed a Adraa (Edraa or Aedraa), Adschma (Adshma), and Marib.

Until recently, only a few trained observers had examined the site of the largest of these, the Marib Dam. This barrier, called Sudd al-Arim by the Moslems, is ranked as the largest of the ancient dams in southern Arabia. According to one report, it was located on the Wadi Sadd (Saba) near Marib and roughly 320 kilometers (200 miles) north of Aden. Approximations of dates related to the dam, as well as its size, vary among the works of historians. It is mentioned in an inscription dating from the year 750 B.C. Some investigators believe that Lokman, King of the Sabaeans in about 1,700 B.C., built this dam on a wadi at a site approximately 10 kilometers (6 miles) from the city of Saba. Others say it was constructed on the Wadi Dhana (Danna or Denne) in the period around 1000 to 700 B.C., as the Kingdom of Sheba approached its peak.

One account described the dam as 3.2 kilometers (2 miles) long, 37 meters (120 feet) high, and 152 meters (500 feet) wide at the base, with a volume of several million cubic meters of rock. But another, much more plausible, version tells of an embankment only a fraction as large and composed of earth. This presumably is the dam whose remains can still be seen today, at a site on the Wadi Dhana about 5 kilometers (3 miles) upstream from Marib. Arabs who examined the ruins in 1936 and 1947 described this structure as 650 meters (2130 feet) long, with five "spillways." Also, 14 irrigation channels were said to be associated with the reservoir. The explorers were impressed with the exceptional quality of the masonry of the diversion works.

Some of the apparent discrepancies in the early historical records are possibly explained by the existence of several dams. Evidently, there was a series of barriers that regulated flows in the wadis which drain the eastern slope of a mountain range in Yemen. The principal structure in the series was said to be the Marib Dam, which functioned as the central control for distribution of the mountain waters. The hillsides at the site were excavated to form intakes for diversion of water to the fields in the vicinity. The role that the Marib Dam played in the prosperity of the region is clear from the reference in the Koran to "great gardens of the Sabaeans."

Around 500 B.C., the dam on the Wadi Dhana was enlarged to make it about 7 meters (23 feet) high and 610 meters (2000 feet) long. Each face was built on a 1 to 1 slope. The upstream face was protected with a lining of mortared masonry. A later major enlargement raised the Marib Dam's height to 14 meters (46 feet). This was accomplished evidently at some time after the Sabaean rule ended in 115 B.C., giving way to the power of the Himyarites.

Major canal intakes at the abutments of the dam are well preserved. The outlet facility at the right abutment served a hillside canal, while the works at the left end of the dam diverted water into a canal built on an embankment. This transitioned to a more conventional aqueduct farther downstream. Remains of these conveyance facilities are still visible at the site. Between the left outlet structure and the left abutment was a wall which evidently functioned as a spillway. The joints in its masonry appear to have been filled with a bituminous material. The stone diversion works were formed by large blocks so neatly trimmed that they fitted closely at the joints. These hewn stones were placed crosswise at intervals to assure inter locking of their courses. The stones were further fastened by pins (lead rods) about 100 millimeters (4 inches) long and 1,000 square millimeters in section. These pins were inserted into holes drilled in the stones to a depth of approximately 50 millimeters (2 inches). The adjoining block in the next higher course was drilled and positioned so that the upper end of the pin extended into it as the stones were brought together.

Some accounts say that no mortar was used in the masonry joints, even though the engineers and artisans in Yemen were acquainted with the use of mortar. This does not agree with another report which described masonry so tightly bonded by mortar that not a single stone could be pulled out. In fact, a mortar coating reportedly was placed on the crest of Marib Dam for weatherproofing. These careful construction measures were evidently successful to some degree. Remnants of the diversion works more than 15 meters (50 feet) in height have survived the attack of the elements. Other sections of the structure are gone, perhaps destroyed by a violent storm during Abyssinian rule in the sixth century A.D.

King Sharahbil Yafur reportedly had the dam rehabilitated in 449 A.D., but in 450 A.D. floods again ruptured the structure. The dam was restored. Then in 542 A.D., during the rule of the Abyssinian Viceroy Abraha, another major breach occurred. The last known inscription relating to the structure was made in that same year. It reported that the Viceroy had ordered repairs of the dam and had requested large quantities of provisions for the many workers, including 200,000 sheep and goats, 50,000 sacks of flour, and 26,000 crates of dates. Evidently the reconstruction was completed expeditiously. Historians tend to agree that the final disaster struck the dam soon thereafter, and the plain of Saba reverted to desert. There are some scholars who say that the last failure of the dam was between 542 and 570 A.D. Others believe that this happened in the seventh century A.D. The loss of the dam has been ascribed to various causes, ranging from volcanic activity to earthquake to neglect. The last may be most likely.

Siltation of the reservoir was undoubtedly a problem. Some evidence of a rock structure has been uncovered at the foundation of the dam near the middle of the valley that indicates a facility for sluicing or low-level diversion.

Presumably, sediments were removed by this means or by crews of laborers. Some observers, on examining the layers of deposits in the reservoir, have suggested that water storage capacity was eventually so reduced by silt encroachment that the dam was overtopped and breached.

About the dam's death, the *Encyclopedia of Islam* says "There is hardly any historical event in pre-Islamic history that has become embellished with so much that is fanciful, and related in so many versions, as the bursting of the Marib dam - Sudd al Arim." The Koran recalls that "the people of Saba had beautiful gardens with good fruit. Then the people turned away from God, and to punish them, He burst the dam, turning the good gardens into gardens bearing bitter fruit."

Some analysts of ancient times in the Middle East have ascribed the fall of the South Arabian kingdoms to the breaking of the Marib Dam. Mor likely, the decline of these governments had begun many years earlier. The dam was neglected and suffered from leakage. The loss of the vital water facility was a critical adversity for an already weakened people.

While the Marib Dam is recognized as the outstanding structure among the waterworks of ancient Yemen, the ruins of other impressive barriers can be seen in the region. Two which deserve mention, at Adraa and Adschma, were built in narrow gorges; and each may have been as high as 15 to 20 meters (50 to 65 feet). These were made of stones and soil, confined by nearly vertical masonry walls at the upstream and downstream faces. The cut stones in the outer walls of the dam near Adraa were stepped and plastered. It also had two parallel core walls made of uncut stones. These walls were evidently erected to the full height of the barrier. The gap of 2 to 3 meters (6 to 10 feet) between them was filled with clayey soil, apparently without any stones. A composite section such as this, with outer embankment zones built against a relatively impervious core, would indicate that the constructors had some understanding of the basic requisites of design. This view is also supported by the still existing outlet works with the intake on the upstream side connected to a conduit placed through the masonry walls. Here, as well as at the dam near Adschma, diversion was made into hillside canals. Remains of these canals can be seen today. The histories of these dams are incomplete. Their origins are unknown, but both structures may have failed in the seventh century A.D. when war and religious strife swept the land.

In Iraq (Mesopotamia), some of the earliest dams are attributed to the Assyrian King Sennacherib (705-681 B.c.), who ordered their construction to serve his capital city of Nineveh. Among these were two masonry structures at Ajilah on the Khosr River. The more important one had a length of about 240 meters (787 feet) and a height of at least 3 meters (10 feet). The Khosr River was also dammed farther upstream near Qayin, and another barrier was built at Bavian on the Atrush River for diversion of its waters to the Khosr.

Soon after the beginning of the sixth century B.C., the Babylonian King Nebuchadrezzar II**,** the Nebuchadnezzar of the Bible, constructed a dam at Abbu Habba, south of Baghdad. He is also credited with construction of the "Royal Canal" running between the Tigris near Ctesiphon and the Euphrates at Sippara. This channel was reported to be of such large dimensions that it accommodated any of the ships that sailed in those days.
Herodotus recorded that a basin at Sippara was almost 8 kilometers (5 miles) around and walled with stone. Other important canal projects were accomplished under the direction of Nebuchadrezzar, and important advances were made in design. Babylon's eastern canal was "walled up from the bottom," indicating that the lining of canals was accepted practice in that era. Stone dams were erected to turn the river water into the canals, and gates were operated to control the flow.

In 539 B.C., Cyrus the Great, King of Persia, defeated the Babylonian Army commanded by Crown Prince Belshazzar, son of Nebuchadrezzar. According to generally accepted accounts, Cyrus then built an earth damon the Diyala, a tributary of the Tigris, to create diversion works for irrigation. He reportedly had 30 canals excavated to establish an extensive water distribution network.

In Persia, the Achaemenians built dams on the River Kur south of Persepolis. Most of this work was done in the sixth or fifth centuries B.C., when their power was at its peak. The Persian King Darius the Great (521-485 B.c.) had three gravity dams built on the River Kur near his palace at Persepolis.

The Kingdom of Qataban in South Arabia covered the region now called Bayhan. Its capital was at Timna. The Qatabanians thrived during the first five centuries B.C. Their prosperity was owed largely to waterworks of remarkable scope. A canal about 24 kilometers (15 miles) long served between the village of Beihan al-Qasab and a point north of Hajar bin Humeid. This was one of several such facilities for conservation of local runoff. These conveyance works were operated in conjunction with masonry reservoirs and stone gate structures which regulated flows to the delivery systems.

When Qataban was at its zenith, the countryside bordering the Wadi Beihan was nourished by the waters of a skillfully engineered irrigation system. The chronology of this vital network has been determined closely from inscriptions on some of the regulating structures, with dates of the facilities varying from about the fifth century B.C. to the first century A.D. This evidently means that even after the fall of the Kingdom of Qataban, after 25 B.C., the water project on the Wadi Beihan was maintained by its successors, the states of Hadhramaut, Saba, and Dhu-Raidan. When these kingdoms in turn faded away, the irrigation systems also crumbled.

Other dams created in antiquity were of impressive dimensions. On the island of Ceylon, for example, Sinhalese engineers established daring precedents in earth fill construction. Many of the ancient waterworks in Ceylon were built in its northern and eastern regions. Ruins of some of these facilities can still be seen near the old capitals of Anuradhapura, Polonnaruwa, and Tissamaharama. The Sinhalese kings aggressively advanced water development in lands under their control. After their immigration in the fifth century B.C., the Sinhalese implemented irrigation plans which supported a flourishing economy until these people were overcome by new invaders in about 1200 A.D.

Embankments of great length were constructed by the Sinhalese to for reservoirs or "tanks" of large capacity. The Kalabalala Tank was formed by an earthfill 24 meters (79 feet) high and about 6 kilometers (3.5 miles) long. Its perimeter measured 60 kilometers (37 miles). The storage was used to supply irrigation systems around the city of Anuradhapura.

Among the oldest reservoirs in Ceylon are those of Basawakkulam (430 B.C.), Tissa (307 B.C.), and Nuwara (first century B.C.) near Anuradhapura. The earth fills forming these impoundments were relatively low but very long. They were restored during the latter part of the 19th century A.D.

In 331 B.C., Alexander the Great led his forces into the Valley of the Tigris. The records of his campaign indicate that dams on the river had to be partially removed to permit passage of his fleet. These have been described as massive rubble-masonry weirs which served as diversion works for canal intakes. Other accounts refer to Alexander's removal of embankments which blocked his way on the Tigris. Possibly, he encountered both kinds of barriers during his advance. As he consolidated his gains, he presumably had the dams repaired. His chroniclers have given enthusiastic narratives about the irrigation of the conquered land.

In Baluchistan (Pakistan), ruins of pre-Aryan dams have been discovered near Lakorian Pass and in the Mashkai Valley in the southern region of that country. In the centuries following the Aryan invasions in the middle of the second millennium B.C., irrigation on the subcontinent was expanded. One of the outstanding structures was the Sudarsana Dam built near Girnar in Kathiawar during the reign of Chandragupta, the first emperor of India (322-298 B.C.). Rock inscriptions describe this "pleasant looking" barrier and record two disasters which struck it. In one of these "by a breach, four hundred and twenty cubits long, just as many broad (and) seventy-five cubits deep, all the water flowed out, so that (the lake), almost like a sandy desert, (became) extremely ugly (to look at)." The Sudarsana Dam is known to have survived until at least 457 A.D., but its fate after that is obscure.

In about 240 B.C., a stone-crib dam about 30 meters (98 feet) high and almost 300 meters (1000 feet) long was built on the Gukow River in the Shansi Province of China. However, not many other dams were constructed in that country in the early centuries.

The Nabataeans built dams in the Negev desert in the vicinity of the present Israeli-Jordanian border. Outstanding examples were a rockfill 14 meters (46 feet) high near the old capital city of Petra (Jordan) and gravity dams in the Wadi Kurnub, 38 kilometers (24 miles) southeast of Beersheba (Israel). Two of the gravity structures remain intact today. Most of the others constructed in the region in that era were allowed to deteriorate and fall into disuse. The dependent farms then faded into barren wasteland.

Today the central Negev has many ruins that testify to the effective water projects that sustained its farms in Nabataean and Roman times. Agriculture thrived there between the second century B.C. and the seventh century A.D. Low dams and irrigation ditches intercepted and distributed the limited runoff.

The ancient city of Ovdat (Aboda) is in a farming district in the central Negev. It was built by the Nabataeans in about the second century B.C., but most remnants of the first construction have been erased by Roman and Byzantine and later activity. Many thousands of dams reportedly can be found in an area of about 130 square kilometers (50 square miles) surrounding Ovdat. Practically every controllable wadi in the vicinity was dammed. Most of these barriers were small, up to about 2 meters (6 feet) high. But in the larger ravines, there are traces of dams that must have measured as much as three times this height.

The dams in the Negev served various functions. First among these was the diversion and storage of water. Such structures were erected on the wider and deeper wadis. For example, in the Wadi Ovdat there are ruins of a 4-meter (14-foot) wide barrier composed of large stones and having a curved axis.

Thousands of low dams in the area served as sediment interceptors. These generally were in the smaller wadis. A typical barrier would have been about 2 meters (6 feet) high, 2.5 meters (8 feet) wide, and 46 meters (150 feet) long. These dams were usually stone and earth embankments, with slopes protected by stepped courses of masonry. A series of such structures would extend along a wadi, at a spacing of about 40 meters (130 feet). Eventually, the accumulations of silt between the barriers would form a continuous stairway of alluvium that could be placed in cultivation. Then, by flood irrigation and periodic deposition of more silt, these fields were turned into productive farms. In this way the people of the Negev effected significant accretions to their minimal acreage of arable land.

At about the same time, important waterworks were being developed in Spain. After the Romans gained control of Toledo in 193 B.C., they undertook the transport of water to that city in an aqueduct. A reservoir was created by construction of the Alcantarilla Dam, which was 20 meters (66 feet) high and at least 550 meters (1800 feet) long. The dam is believed to have been built in the second century B.C., on the Arroyo del Guajaraz at a site 20 kilometers (12 miles) south of Toledo. It was essentially a masonry and concrete mass buttressed on its downstream side by an earthfill. Today the dam is in ruin.

The dam of Alcantarilla is considered to be the oldest in Spain and is possibly the earliest Roman dam. It is of cruder construction than those of the same type built later at Merida, such as the Proserpina Dam. Unlike the latter, the Alcantarilla Dam had no buttresses supporting its upstream face. On that side there were two parallel rubble-masonry walls each approximately 1 meter (3 feet) thick, separated by a space of about 0.6 meter (2 feet) which was filled with concrete. Cut-stone blocks protected the upstream face. To bolster the composite wall against the water load, its downstream face was buttressed with an earth fill 14 meters (46 feet) thick at the crest of the wall and with a slope of 3 to 1. Deep openings at each abutment are evidence that substantial spillways were incorporated in the structure.

Today both the masonry wall and the embankment of the Alcantarilla Dam are breached over a central distance of about 200 meters (650 feet). This suggests that the masonry mass may have been toppled upstream by the pressure of the earthfill as the reservoir level was being lowered.

The Romans were also active in southern France, where Glanum was one of their very early settlements. An aqueduct conveyed water to Glanum from a reservoir impounded by a low curved dam. This structure is believed to date from the first century B.C., or possibly a little later. In 1891 A.D., a new dam was constructed on the ruins of the Roman barrier, concealing evidence of the earlier works.

The Roman dam near Glanum was reported to be approximately 6 meters (20 feet) high, with a crest length of possibly 9 meters (30 feet). It was a composite of two masonry walls, each slightly thicker than 0.9 meter (3 feet), and separated by a space of about 1.5 meters (5 feet), which was probably filled with soil and stones. The thin section, only about 3.6 meters (12 feet) thick and rising to a height of 6 meters (20 feet), must have been dependent upon its curvature in plan to assure its stability against water forces.

The First Millennium A.D.

In Spain, a little more than 100 years later, work was begun on some of the finest Roman dams. These were near the town of Merida, which is noted today for its impressive Roman ruins. Six kilometers (4 miles) north of Merida, early in the second century A.D., the Romans built the Proserpina Dam **(fig. 1-3)**, 19 meters (62 feet) high above its foundation and 427 meters (1400 feet) long.

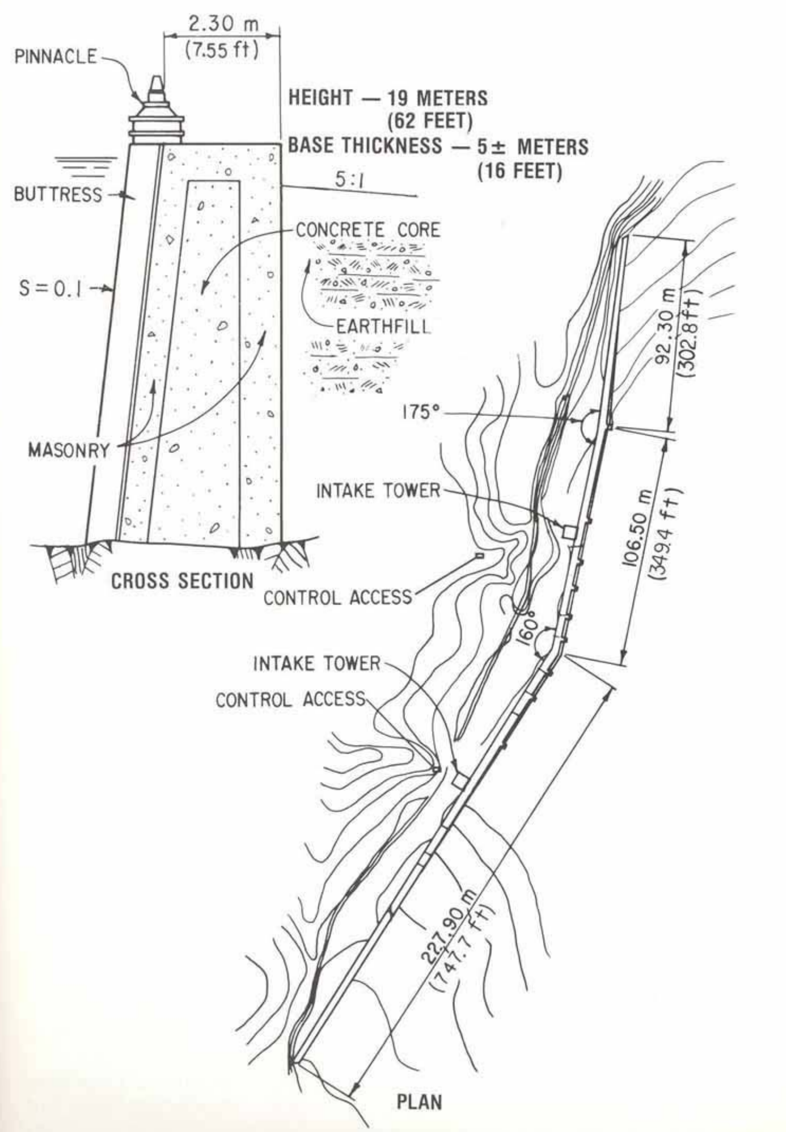


Figure 1-3.—Proserpina Dam, plan and cross section. P-801-D-79289.

The Proserpina Dam has been ranked as a classic among structures of its type. An upstream section is comprised of a concrete core sandwiched between two masonry walls. The original thickness of the composite wall has been estimated to be about 3.75 meters (12.5 feet) at the top. Some reports indicate that this may have been as little as 2.1 or 2.4 meters (7 or 8 feet) in a few places. At the foundation, the thickness may have been as much as 5 meters (16 feet). The upstream face is battered steeply at 1 to 10 while the downstream masonry face is vertical. The wall extends about 6 meters (20 feet) into the foundation. Following the precedent set at A1cantarilla Dam, an earthfill was placed against the downstream side of the wall. This slopes from the crest to intersect the natural ground at a maximum distance of about 60 meters (200 feet).

A basic difference between the Proserpina and A1cantarilla Dams is that masonry buttresses were erected at the upstream face of Proserpina to provide resistance against overturning. Lack of this feature was the weakness that led to the collapse at A1cantarilla.

The records do not reveal much about the nearly 2,000-year lifespan of Proserpina Dam. It is assumed to have suffered long periods of neglect. There is information on repairs and modifications accomplished in the years 1617, 1689, and 1791. This would indicate that the reservoir has been in possibly continuous service for nearly 400 years. It has not suffered serious impairment by siltation. Major repairs were made in 1942, including rehabilitation of the masonry. Water is still supplied via a Roman aqueduct between the dam and Merida.

The A1cantarilla and Proserpina Dams had large capacity spillways, testifying to the Roman understanding of the vulnerability of such structures to uncontrolled floods.

The water supply for Merida was enhanced at a later date by construction of the Cornalbo Dam **(fig. 1-4)** 16 kilometers (10 miles) northeast of the city on the Rio Albarregas. It is a more sophisticated structure than its predecessors in that area. Although the history of this dam is fragmentary, there appears to be general agreement that it was inoperable for extended periods in medieval times. Then in the 18th century it was placed back into service. It is one of the oldest dams still operational and among the largest constructed by the Romans.

Figure 1-4.—Cornalbo Dam (Courtesy, Comité Nacional Español, ICOLD). P-801-D-79290.

The Cornalbo Dam has an essentially straight longitudinal axis. It is approximately 24 meters (79 feet) high above its foundation and 200 meters (650 feet) long. In cross section, the structure is trapezoidal. The crest thickness is flared from 7 meters (22 feet) at one abutment to more than 12 meters (40 feet) at the other. The maximum thickness at the foundation is about 118 meters (387 feet).

The core of the dam is made up of masonry walls which form interconnected boxes that were filled with stones or clay. This core was then enclosed in an earth embankment with a 3 to 1 downstream slope and a 1-1/2 to 1 upstream slope with masonry revetment for protection against wave wash. Much of this original facing was replaced when the dam was rehabilitated in 1936.

The Romans built many stone dams throughout their empire. These were usually composed of mortared cut-stone masonry of great durability and impermeability. The one built at Subiaco, about 50 kilometers (30 miles) east of Rome, by Emperor Nero in the first century A.D., lasted nearly 1,300 years, as testified by an official account of its failure.

The Romans also recognized the need for soil conservation. Near the coast of Tripolitania (Libya), several wadis draining the north slope of the Jebel Nefuza Mountains discharge large volumes of silt into the Mediterranean during the flood season. Three important cities of the Roman era Leptis Magna, Oea, and Sabratha - were built near the lower reaches of these watercourses. The complex of masonry dams which the Romans erected in the wadis was designed for two purposes - water supply for the cities and protection of the land from erosion.

A Roman dam deserving mention was built in about the second century A.D. near Kasserine, 217 kilometers (135 miles) southwest of Tunis. It is a masonry-faced structure with a core evidently composed of earth and rubble. Cut-stone blocks with mortared joints were used in the facing. The upstream face is vertical for its full height of 10 meters (33 feet), while the downstream side is stepped down from the crest through six courses of masonry and then vertical in the remaining 3.8 meters (12.5 feet) to the base. The thickness varies from roughly 4.9 meters (16 feet) at the crest to 7.3 meters (24 feet) at the base. In plan, the structure is curved but not in a true circular arc. It is about 150 meters (500 feet) long.

Two noteworthy Roman dams were built in Turkey, the one at Orlikaya, 190 kilometers (118 miles) northeast of Ankara, and the Cavdarhisar Dam, 210 kilometers (130 miles) south of Istanbul. The former was 16 meters (52 feet) high and 40 meters (131 feet) long; and the latter was 7 meters (23 feet) high and 80 meters (262 feet) long. These structures were of similar design, each comprising an earth core enclosed by two vertical masonry walls. Attempt was made to seal the joints between the stones with lead. In each case, the total thickness of the composite wall from face to face was about 5.5 meters (18 feet).

Another early gravity barrier was the AI-Harbaqa Dam 70 kilometers (43 miles) southwest of Palmyra (Syria). It is 18 meters (59 feet) high and 198 meters (650 feet) long. The structure has endured through the many centuries, but the reservoir is filled with silt.

Among the nations of the Orient, Japan has a continuous history of dam building dating far back into antiquity. Its oldest notable dam is the Kaerumataike earth embankment constructed in 162 on the Yodo River near the one-time capital city of Nara. Its dimensions: 17 meters (56 feet) high and 260 meters (853 feet) long.

About 100 years later, the Persian King Shapur I (241-272) undertook improvement of the irrigation projects in Khuzestan (Iran) using the labor of Roman soldiers whom he had captured. One of the most impressive structures erected by these prisoners was the dam-bridge extending approximately 550 meters (1800 feet) across the Karun River near Shushtar, in about 270.

Other dams built by the Romans have been found in Syria. The most impressive early construction in that country was 13 kilometers (8 miles) southwest of the city of Horns where the River Orontes was dammed in 284 to create the Lake of Horns. The core of the barrier was of basaltic rubble masonry, cemented with a strong mortar. Cut basalt stones were placed on both faces of the dam, and the joints were mortar sealed. The finished structure was 6.1 meters (20 feet) high, with a thickness varying from 7 meters (23 feet) at the top to approximately 20 meters (66 feet) at the bottom. This Roman dam survived and provided service for 17 centuries. In 1934 a new and larger dam was superimposed on the ancient one.

The engineering of dams also continued to advance in India and Ceylon. Many earth fills were built to create irrigation reservoirs, or "tanks". One of the largest was the Kalaweva Tank in Ceylon, built in 459. Its embankment was about 19 kilometers (12 miles) long.

Byzantine Emperor Justinian (527-565) gave impetus to development of the water supply for Constantinople (Istanbul). Eventually, eight dams were built in the vicinity. Four are still in operation. The largest of these im pounds the 617,000 -cubic-meter (500-acre-foot) Btiyuk Bent on a tributary of the Kiathene Deresi River about 14 kilometers (9 miles) north of the city. This is a rubble-masonry gravity dam faced with cut stone. It has a height of 12.5 meters (41 feet), a length of 76 meters (250 feet), and a base thickness of 10 meters (33 feet).

On the Turkish-Syrian border near the city of Daras, the engineer Chryses from Alexandria, under the direction of Justinian, built a dam which was noteworthy for its curvature in plan. It is regarded by some historians as the first known arch dam. Evidence of its existence was documented in about 560 when Daras was a strategic place at the frontier with the Persian empire. The records indicate that a flood control dam was constructed on a tributary of the Khabur River just outside the walls of the town. The steep abutments were notched to assure firm anchorage of the arch, and gates were provided for flood regulation. However, nothing in the documents or at the river site gives any useful clue as to the structural dimensions. The remnants eroded away long ago.

One of the earliest dams in China is believed to have been built in the year 833. Its name is Tashanyan and it was built on the Zhang Xi River near Ningbo. The dam is a gravity type structure 27 meters (88 feet) high and is still being used for irrigation.

Many of the other dams built in the Middle Ages have lasted a long time. One of the more remarkable is a rubble-masonry weir on the Rio Guadal quivir in Cordova, Spain. Dating back to about 900, it is regarded as probably the oldest remaining Moslem dam in that country. The weir has deteriorated significantly. Pieces of its masonry are scattered in the river channel. But enough of the structure survives to mark its zigzag alinement, totaling about 427 meters (1400 feet), across the stream immediately down stream from the Puente Romano (Roman Bridge). In addition to its original functions of water supply and mill operation, the pool at this dam has protected the bridge piers from erosion. The parts of the weir still standing suggest that its height and its thickness were each about 2.5 meters (8 feet).

In the year 960, the Band-i-Amir Dam was erected on the River Kur in Persia. The masonry structure still stands, but its function has been impaired by siltation. It has a height of 9 meters (30 feet) and a length of 76 meters (250 feet). The downstream slope is about 1 to 1. The dam evidently was built entirely of cut stones with mortared joints reinforced by iron bars anchored in lead. This followed the same practice used in the dam on the Atheim River near Baghdad.

At about the same time, important dams were being developed in southern India. The Moti- Talab Dam, an earth fill structure near Mandya (Mysore), was built in the 10th century and is still functioning today. It is 24 meter (79 feet) high and 157 meters (515 feet) long. The unique cross section has a broad crest about 27 meters (90 feet) wide and has steep slopes of 2 to 3 upstream and I to I downstream.

The Period 1000 to 1600 A.D.

The engineers of India developed a design for earthfill dams with relatively steep slopes protected by cut-stone facing. An outstanding example is the 16-kilometer (l0-mile) long Veeranam Dam, erected in the period 1011 to 1037.

Also in the 11th century, Indian engineers created a reservoir with an area of 650 square kilometers (250 square miles) in a valley about 32 kilometers (20 miles) southeast of the city of Bhopal (Madhya Pradesh), in central India. Evidence still remains of this great Bhojpur Lake, impounded by two earth dams covered on both slopes with immense blocks of cut stone. The project reportedly was developed by Raja Bhoj of Dhara. Flow of the holy River Betwa was augmented by diverting the River Kaliasot into it.

Two natural gaps existed in the circle of hills that enclosed the basin. The width of opening was about 90 meters (300 feet) at one site and 460 meters (1500 feet) at the other. To close these gaps, the Raja had barriers constructed that were said to be impressively watertight. These earth fill dams were faced with un-mortared stones fitted together skillfully by the Indian masons. The higher embankment, which filled the smaller gap in the hills, had a height of about 27 meters (90 feet) and was 92 meters (300 feet) long, with a base width of 92 meters (300 feet). In the wider opening, the Raja's forces built a dam approximately 12 meters (40 feet) high and 30 meters (100 feet) wide at the crest.

A spillway was excavated in the rock of a saddle in the hills. Water stains on the spillway sides mark the maximum reservoir level at about 1.8 meters (6 feet) below the top elevation of the dams. The design of the spillway and its successful functioning for several centuries attest to the talents of the engineers assigned to the project.

Five hundred years after the reservoir was placed in operation, Shah Hussain breached the higher dam to drain the lake so that its fertile bed could be opened to cultivation. According to traditional accounts by natives of the area, a large work force took 3 months to remove the barrier. The longer dam survived to continue diversion of the Kaliasot into the Betwa River.

In the first 15 centuries A.D., the Japanese built about 30 dams higher than 15 meters (49 feet). All were earth fills. One of the most outstanding was the Daimonike Dam, erected in 1128 near Nara. It was about 32 meters (105 feet) high and 79 meters (259 feet) long.

In the same century, the Sinhalese were setting new records in Ceylon. An earthfill structure length of 18 kilometers (11 miles) was attained at Padawiya Dam 60 kilometers (37 miles) northeast of Anuradhapura. The embankment was built to a height of approximately 21 meters (70 feet). The crest was 9 meters (30 feet) wide, and the maximum base width was about 61 meters (200 feet). Slope facing consisted of cut stone.

While the Asians were making important advances in embankment construction, many European engineers continued to build masonry barriers. One of these was the Almonacid de la Cuba Dam **(fig. 1-5)** on the Rio Aguavivas about 40 kilometers (25 miles) south of Zaragoza, Spain. It probably dates from the 13th century A.D. and is judged by some historians to be the oldest surviving Christian-built dam in Spain. The original structure was made of rubble masonry bonded with crude lime mortar and enclosed by a facing of cut stones. Its estimated height was 29 meters (95 feet), and its length was about 85 meters (280 feet). The downstream face was composed of large stone blocks placed in tiers and set in mortar.

At an unrecorded date, the Almonacid de la Cuba Dam was heightened. Evidently, this was necessitated by the continuing effects of silting, which eventually encroached on most of the storage capacity. The added section is a mass of crude rubble masonry set in a matrix of stones, earth, and lime mortar. This vertical-faced wall increased the height to about 30 meters (98 feet) and the length to over 100 meters (328 feet). The maximum crest thickness is about 25 meters (82 feet).

The spillway for the original dam was in rock at the left abutment. As part of the enlargement, the spillway crest was elevated by a curved weir.

In 1258, Hulagu Khan led his Mongols into Baghdad and eliminated Arab rule. In the confusion of the years which ensued, most of the ancient public works in that region were reduced to ruin. Nimrod's earth dam on the Tigris was breached, lowering the river level about 8 meters (25 feet). The Nahrwan and Dijail Canals were left inoperable. The rich farmlands bordering the upper Tigris reverted to desert. The ancient barrier on the Sakhlawia branch also was breached, and the irrigation works of western Baghdad fell into disuse.

During the same century, at a site southwest of Tehran in Persia, the Saveh Dam was erected for irrigation of the Mongol-dominated land. The date of its construction has been estimated as between 1281 and 1284. Apparently its main claim to fame is that its reservoir has never held water, although the dam has survived more or less intact. It is a crude rubble masonry gravity structure without any cut-stone facing. With a height of 18 meters (60 feet), and a length of 46 meters (150 feet), it might have been an effective barrier if built on a sound foundation. However, it was placed on river alluvium. The first water entering the reservoir evidently found its way under the dam and left it standing high and dry.

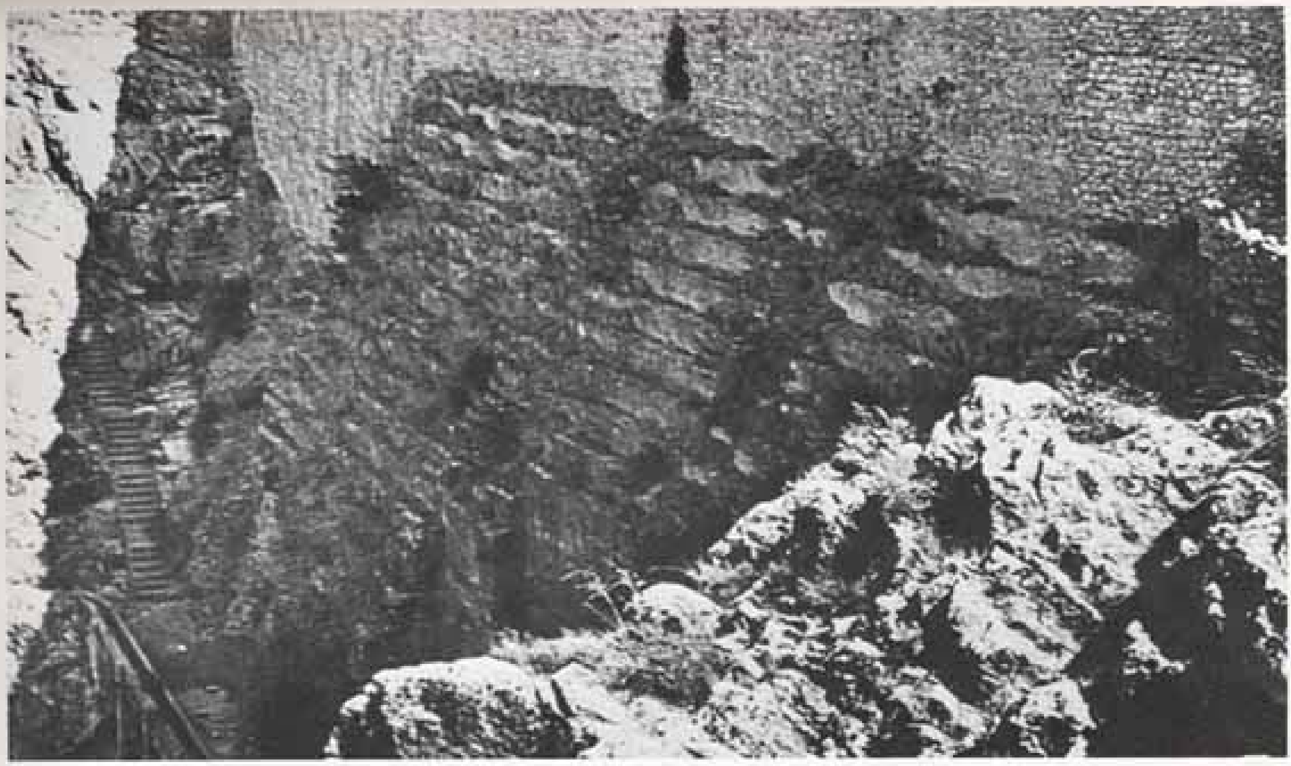


Figure 1-5.—Almonacid de la Cuba Dam (Courtesy, Comité Nacional Español, ICOLD). P-801-D-79291.

Another dam of the same Mongol period in Persia spans a narrow gorge on the Kebar River, about 24 kilometers (15 miles) south of the town of Qum and 170 kilometers (105 miles) southwest of Tehran. Dating from about 1300, it is regarded as the oldest known surviving arch dam. The constant radius of curvature of its downstream face is 38 meters (125 feet). Its height is about 26 meters (85 feet), and its length is 55 meters (180 feet). The crest has a practically constant thickness of 5 meters (16 feet). Materials used in the construction were cemented rubble masonry with mortared stone block facing. The arch was keyed into the rock abutments.

In the year 1384, an arch-gravity dam was built about 5 kilometers (3 miles) west of the town of Almansa in Albacete Province in Spain. This is regarded as the first known arched dam in that country. The original Almansa Dam **(figs. 1-6 and 1-7)** was about 14.6 meters (48 feet) high and curved to a radius of about 26 meters (85 feet) at the downstream side of the crest. Its thickness has been estimated to be approximately 10 meters (34 feet) at the base and about 4 meters (13 feet) at the top. The structure is composed of rubble masonry with a facing of stone blocks. It is anchored securely into the rock foundation.

The Almansa Dam was enlarged in 1586 and again in the years 1736 and 1921. The most prominent addition is an angled wall superimposed upon the top of the original barrier. The wall is 6 meters (20 feet) high, 3 meters (10 feet) thick at the top, and nearly 3.6 meters (12 feet) thick at the base. The lengths of the straight walls on each side of the angle are about 36 meters (118 feet) and 53 meters (174 feet). Almansa Dam is now officially listed as 25 meters (82 feet) high and 90 meters (295 feet) long. The structure is still in sound condition.

A structure generally regarded as the oldest significant dam existing in Italy is the Cento Dam on the Savio River about 30 kilometers (19 miles) south of Ravenna. The year of its construction is estimated to be 1450. It is 71 meters (234 feet) long and about 14 meters (45 feet) thick at the base. The original gravity dam has a vertical upstream face approximately 6 meters (19 feet) high and a crest thickness of just a few feet. A parapet wall added at a later date increased the height by about 1.4 meters (4.5 feet). The Cento Dam is noteworthy for its construction of bricks set in lime mortar within a framework of wood poles.

Until about 500 years ago, very few earthfill dams approached 24 meters (80 feet) in height. Among these were the early embankments in India and Ceylon. Then in 1500, the Mudduk Masur Dam, with a height of 33 meters (108 feet), was constructed in Madras Province in southern India. This embankment height was unsurpassed for about 300 years.

Among masonry structures, an equally impressive record was held by the monumental Alicante Dam **(figs. 1-8 and 1-9)** on the Rio Monegre 18 kilometers (11 miles) northwest of the town of Alicante in Spain. Construction of this barrier, also known by the name of the nearby village of Tibi, was begun in 1580 and then suspended due to lack of funds. Work was resumed several years later and was completed in 1594. Then, for nearly three centuries, this dam was the highest in the world, measuring 41 meters (135 feet) from base to top.

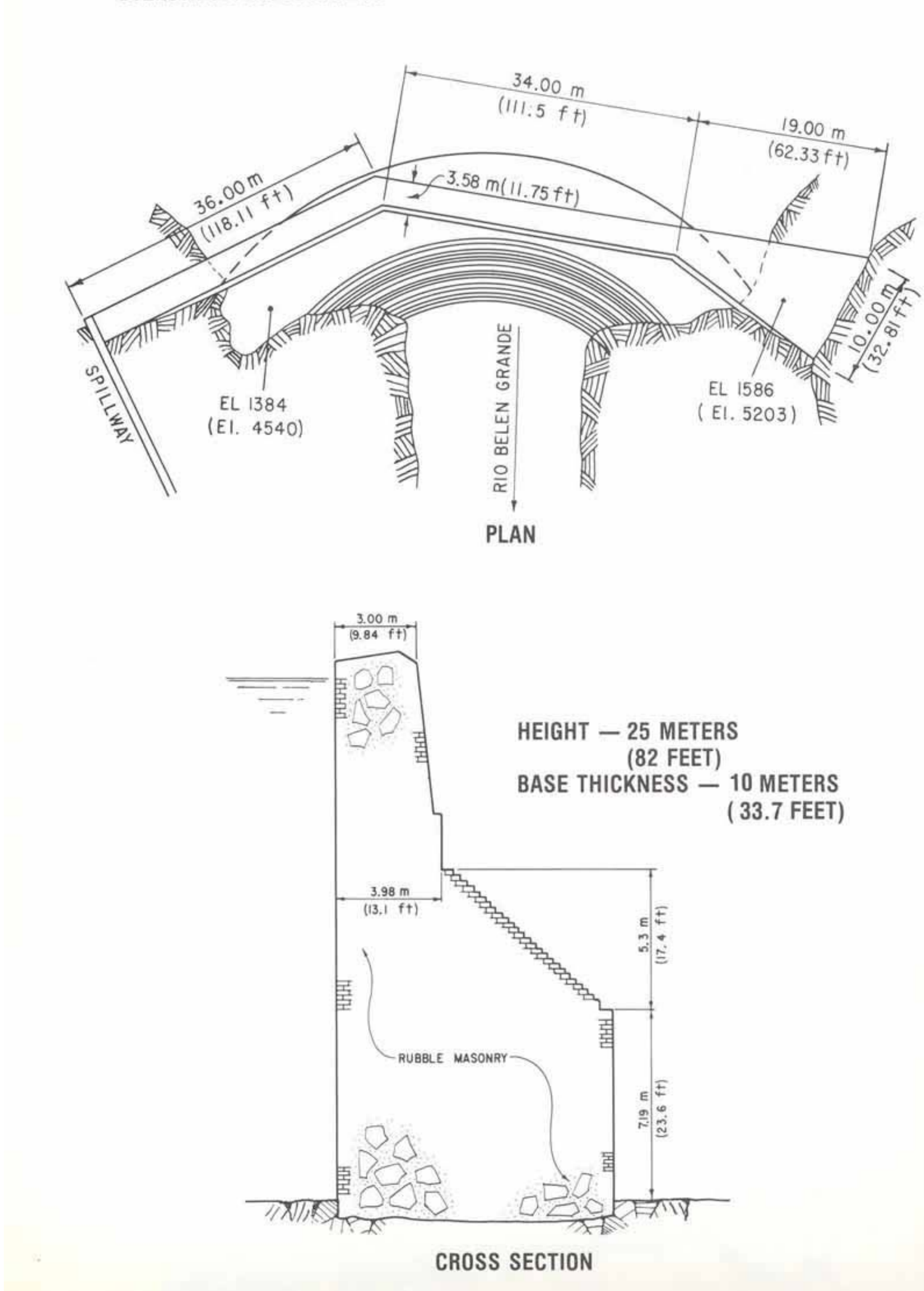
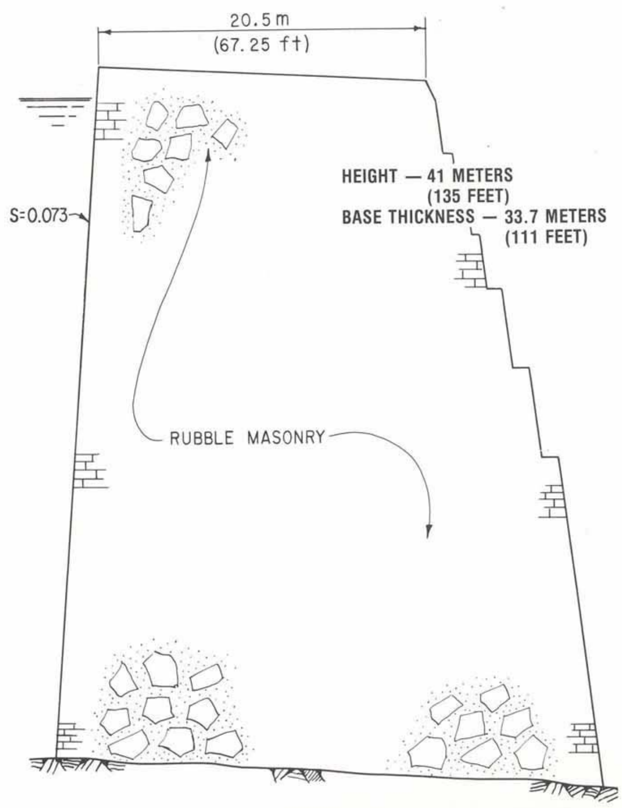


Figure 1-6.—Almansa Dam, plan and cross section. P-801-D-79292.

The dam site in the gorge of Tibi is only about 9 meters (30 feet) wide at the bottom. The structure is composed of rubble masonry set in mortar and faced with large cut stones. The plan is curvilinear, with a total crest length of about 80 meters (262 feet). Structural thickness varies from approximately 20.5 meters (67 feet) at the top to 33.7 meters (111 feet) at the base. Volume of the mass is 36400 cubic meters (47 600 cubic yards).

The Alicante Dam was provided with a de-silting system and a vertical shaft outlet works. These have been closed permanently. Originally there was no separate spillway. Water discharged over the crest and down the stepped masonry face. In 1697, a flood damaged the face; the dam was rehabilitated in 1738. A side channel spillway was constructed later. However, this has not operated often in recent years and has been closed with stoplogs. The dam was enlarged in 1943. Its present height is listed as 46 meters (151 feet).

Figure 1-7.—Almansa Dam (Courtesy, Comité Nacional Español, ICOLD). P-801-D-79293.



ORIGINAL DAM AS CONSTRUCTED—1594

Figure 1-8.—Alicante (Tibi) Dam, cross section. P-801-D-79294.

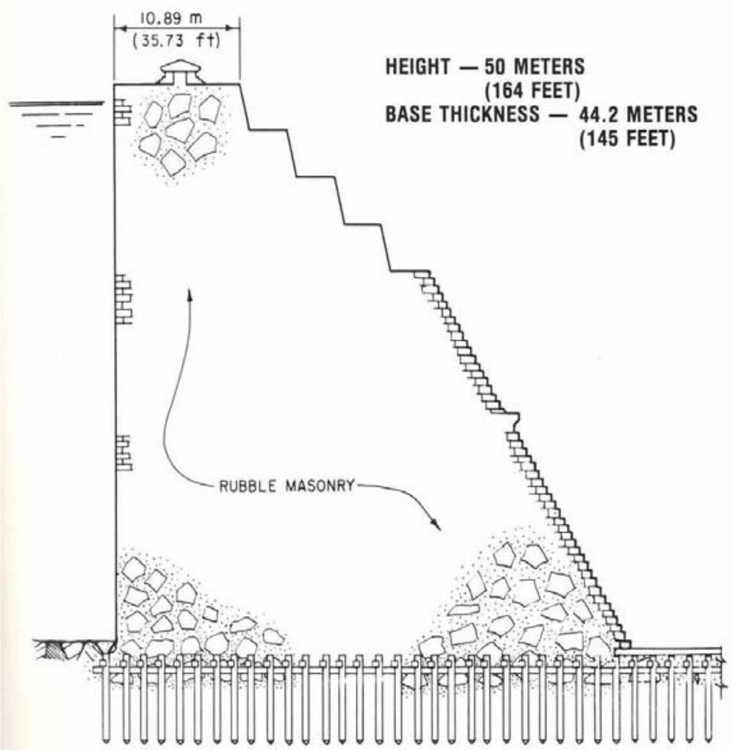


Figure 1-19.—Puentes Dam, cross section. P-801-D-79305.

The Period 1600 to 1800 A.D.

Not far from the Alicante site, the first true arch dam in Spain was built on the Rio Vinalop6 near the town of Elche in the mid-17th century. The Elche Dam **(figs. 1-10 and 1-11)** was constructed of the traditional rubble masonry with cut-stone facing. It was enlarged in 1842. The plan is curved, with a mean radius of 62.6 meters (205 feet) and a crest length of about 70 meters (230 feet). Its height is 24 meters (79 feet). The arch thickness varies from about 9 meters (30 feet) at the top to 12 meters (39 feet) at the base. As at the Alicante Dam, the crest of the Elche structure has served as a spillway and has been damaged by floods.

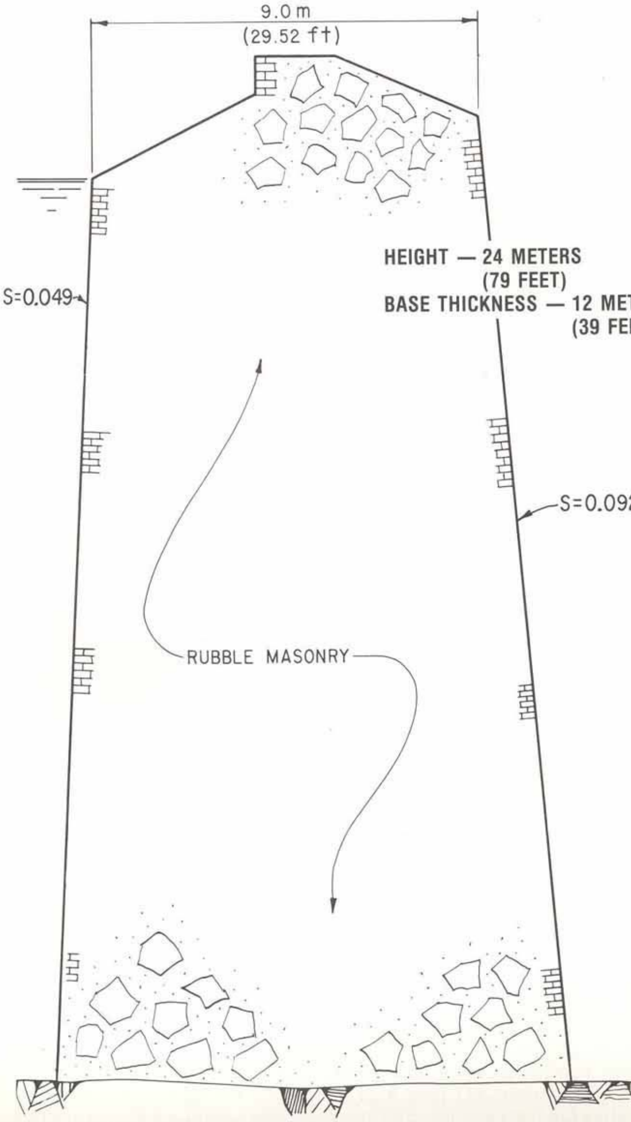


Figure 1-10.—Elche Dam, cross section. P-801-D-79296.

Figure 1-11.—Elche Dam (Courtesy, Comité Nacional Español, ICOLD). P-801-D-79297.

Another arched structure built in the 17th century was the Relleu Dam **(fig. 1-12)** on the Rio Amadorio northeast of Alicante. Its first stage was 28 meters (92 feet) high, with a practically constant thickness of 10 meters (33 feet) and a crest length of about 24 meters (80 feet). The arch was laid out on a mean radius of 65 meters (213 feet). A second stage was added in 1879. This consisted of a crest wall 3.85 meters (12.6 feet) high and 5 meters (16.4 feet) thick, extending the length to 34 meters (112 feet). The many years of overflow have eroded the top of Relleu Dam and dislodged much of the stone surfacing which protected the rubble masonry.

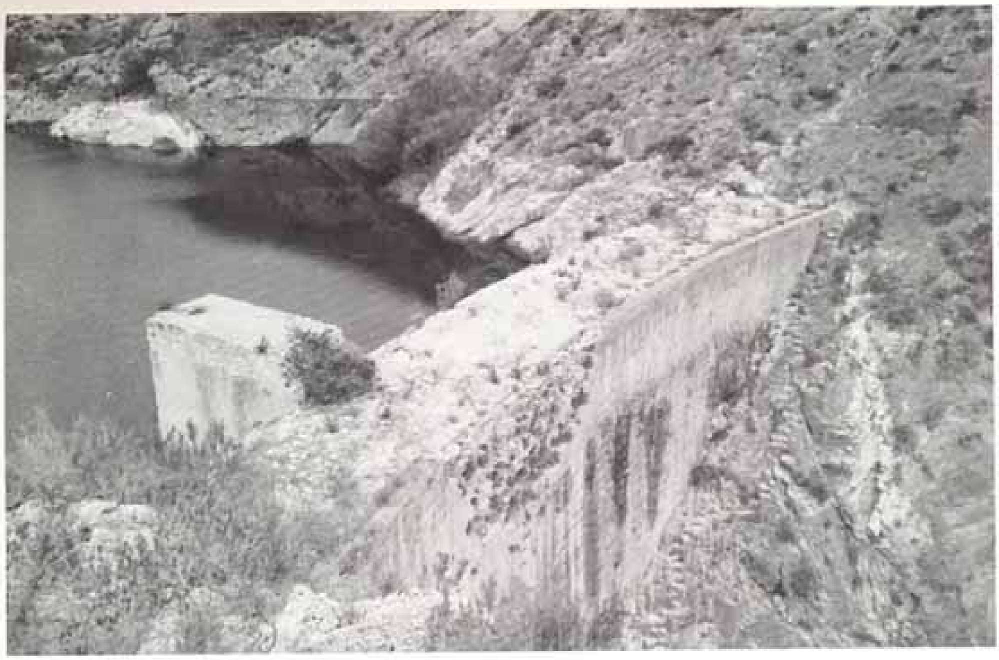


Figure 1-12.—Relleu Dam (Courtesy, Comité Nacional Español, ICOLD). P-801-D-79298.

Early in the 17th century, the Ternavasso Dam was built about 30 kilometers (19 miles) southeast of Turin in Italy. This is an earthfill about 7.6 meters (25 feet) high and 335 meters (1100 feet) long. The top width varies from 5.2 meters (17 feet) to 6.7 meters (22 feet). The vertical upstream face consists of a brick wall approximately 0.6 meter (2 feet) thick, coated with mortar and braced at intervals by buttresses about 1.8 meters (6 feet) thick.

Another Italian structure of the same period is the Ponte Alto Dam, a thin arch on the River Fersina just east of Trento. Regarded as the first arch dam in Italy, it is located on the site of an earlier wood barrier, reportedly erected in 1537 and washed out by a flood in 1542. The initial stage of the Ponte Alto Dam, made of masonry blocks with un-mortared joints, was under construction from 1611 to 1613. It was about 5 meters (16 feet) high and 2 meters (6.5 feet) thick, with a radius of approximately 14 meters (46 feet). In 1752, the addition of a second stage increased the height to 17 meters (56 feet). Subsequent enlargements in 1825, 1847, 1850, and 1887 created a dam which is now 38 meters (125 feet) high. The integrity of the structure is assured by closely fitted stone blocks joined with iron bars.

About 19 kilometers (12 miles) north of Istanbul in the Belgrad Forest are several small masonry dams which are part of the water system for Istanbul. Most of them are hundreds of years old and serve even more ancient conduits delivering water to Istanbul. The first water conveyance from the Belgrad Forest to Istanbul (Constantinople) was accomplished by the Romans, but many of their works are said to have been replaced some time following the Turkish conquest in 1453.

Some of the first dams in the northern American colonies were built for impoundment of water to run gristmills and sawmills. A dam was erected in 1623 to operate the first sawmill in America, on the Piscataqua River at South Windham, Maine. Another provided water for the first gristmill at Portsmouth, New Hampshire.

Meanwhile, Persia was approaching its second peak in dam engineering. During the reign of Shah Abbas II (1642-67), reservoirs were built near Mashhad and Kashan. The famous bridge-dam of Pul-i-Khadju was erected in the same period. Its slotted weir is about 6 meters (20 feet) high, 30 meters (100 feet) thick, and 141 meters (462 feet) long. The dam and the arched bridge are constructed of cut-stone blocks.

During the period 1667 to 1675, the St. Ferreol Dam was built on the River Laudot about 50 kilometers (30 miles) southeast of Toulouse in France. It is an earth fill 36 meters (118 feet) high and 780 meters (2560 feet) long. Three parallel masonry walls extend the full length of the dam, one at each face and one in the center. The upstream wall has a height of nearly 14.6 meters (48 feet) and an average thickness of about 6 meters (20 feet). The one on the downstream side is approximately 18 meters (60 feet) high and has a thickness varying from about 5 meters (17 feet) at the crest to 9 meters (30 feet) at the base. The central wall is 5 meters (17 feet) thick and rises to the full height of the embankment to form the dam crest. The fill between the walls is composed of stones and earth. All materials in the structure evidently were hand-placed.

Between 1714 and 1721, the first large dam in Germany, the Oderteich Dam, was constructed in the Oberharz. It is composed of two stone-block face walls confining a central zone of sand. The wall joints were apparently calked with earth and moss. The structure is 22 meters (72 feet) high and about 151 meters (495 feet) long and has a width varying from roughly 16 meters (52 feet) at the top to 44 meters (144 feet) at the foundation.

In 1747, the Almendralejo Dam was built about 51 kilometers (32 miles) south of Badajoz, Spain. It is also known as the dam of Albuera de Feria. This rubble-masonry buttress dam has survived without any significant deterioration. The original structure was approximately 20 meters (65 feet) high, with a thickness varying from 10 meters (32 feet) to 12 meters (40 feet) from top to base. Later successive enlargements increased the height finally to 23.5 meters (77 feet). Buttresses provide support at the downstream face. The structure is 170 meters (558 feet) long.

The design concepts of the early Spanish dam engineers were conveyed to the colonies in America. However, in some of these lands, water projects had been developed before the conquest. Near Teotihuacan, Mexico, and in the Nepena and Canete Valleys in Peru there are still signs of ancient dam projects.

Hundreds of masonry dams were erected by the Spanish in Mexico. Some of the most remarkable were in the State of Aguascalientes, about 480 kilometers (300 miles) north of Mexico City, where a rubble-masonry buttressed type was popular. These are believed to date from the 18th century. Outstanding examples of these Mexican structures are the Pabell6n, **(fig. 1-13)**, Presa de los Arcos **(fig. 1-14)**, and San Jose de Guadalupe Dams **(fig. 1-15).**

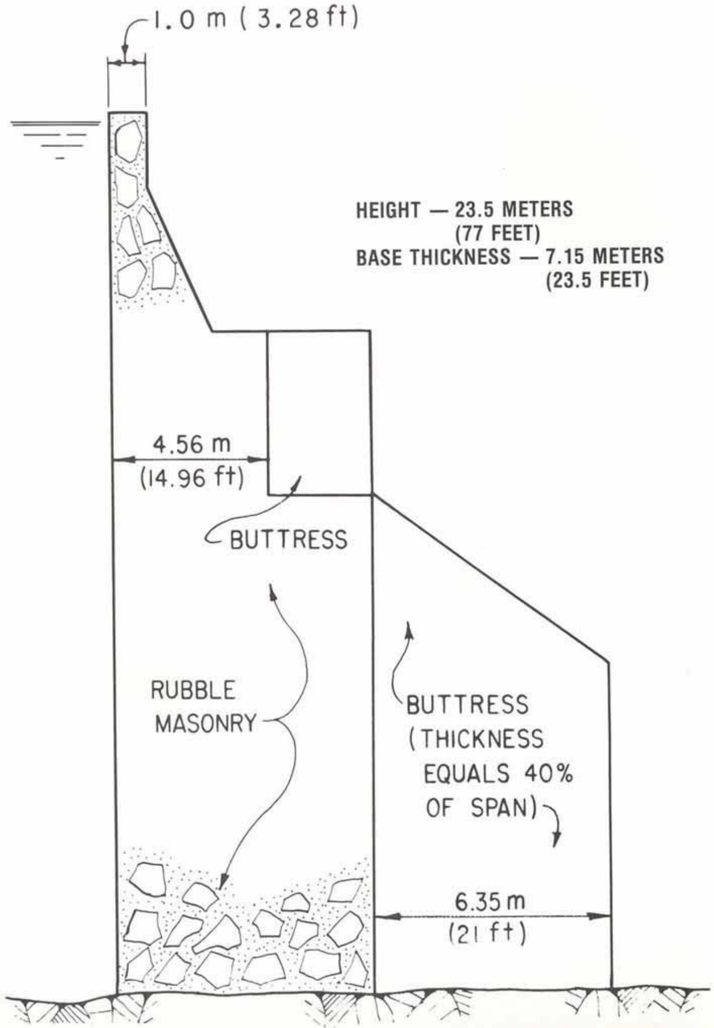


Figure 1-13.—Pabellón (San Blás) Dam, cross section. P-801-D-79299.

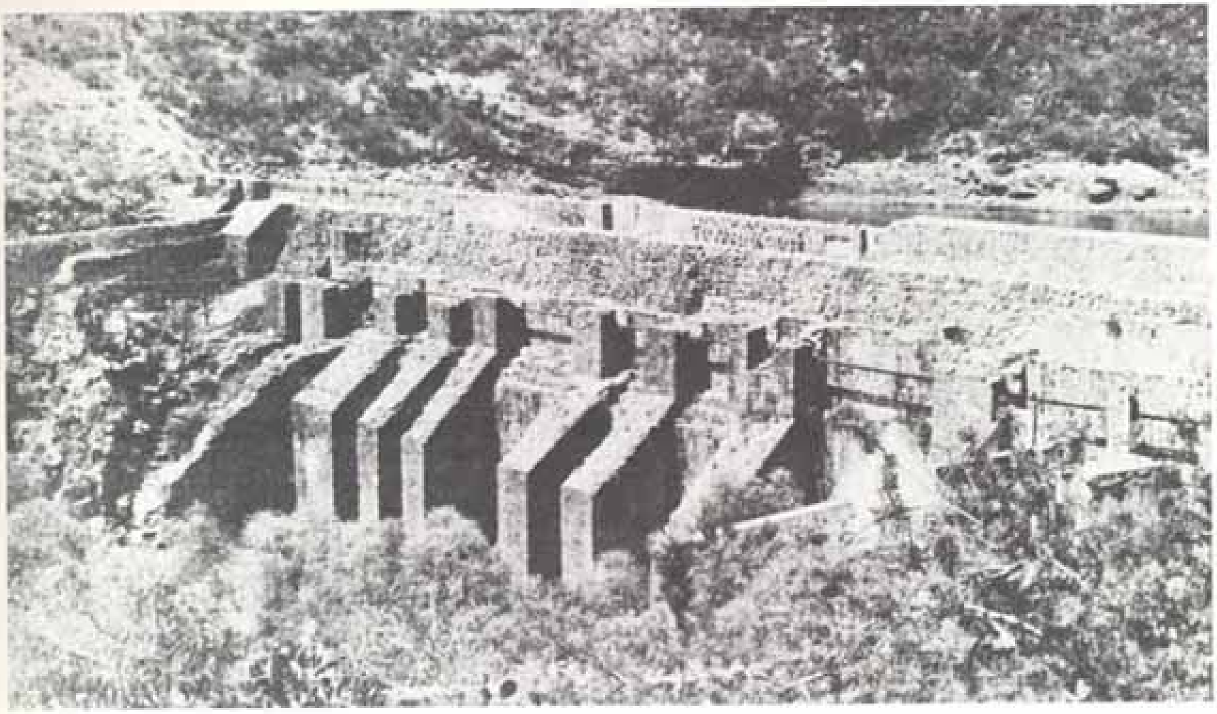


Figure 1-14.—Pabellón (San Blás) Dam (Courtesy of Julian Hinds). P-801-0-79300.

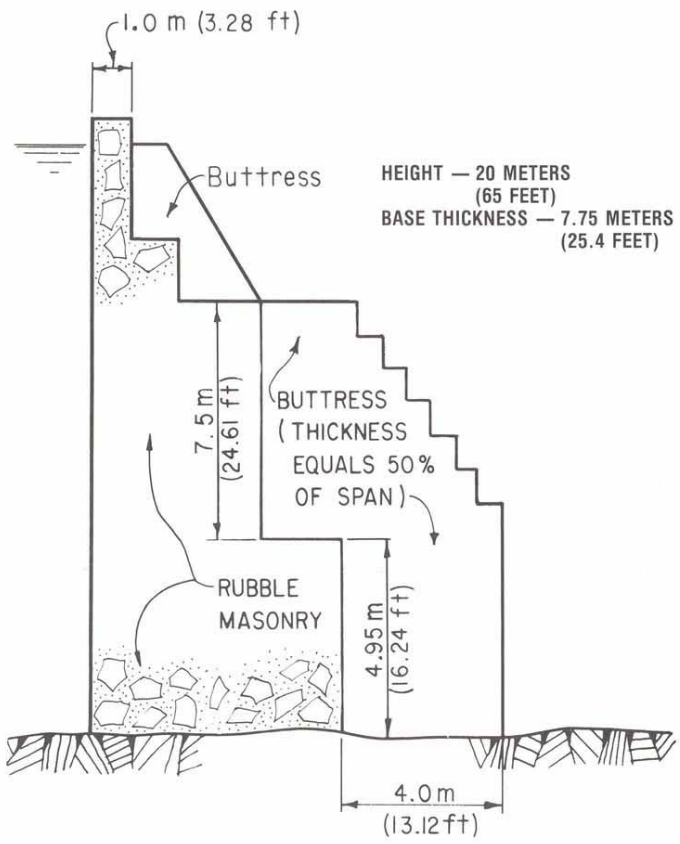


Figure 1-15.—Presa de los Arcos, cross section. P-801-D-79301.

The Pabell6n (San BIas) damsite is on the Rio Pabell6n about 40 kilometers (25 miles) north of the city of Aguascalientes. The dam **(fig. 1-16)** was constructed as a buttressed masonry wall 177 meters (580 feet) long and 23.5 meters (77 feet) high. Originally the dam height was about 17.7 meters (58 feet) and the crest thickness was nearly 4.5 meters (15 feet). That the structure was enlarged is suggested by a change in the masonry design at a level several feet below the crest. The structure was extended by addition of a wall of triangular cross section topped by a parapet. The dam's upstream face is vertical. Maximum base thickness of the masonry mass is approximately 7.15 meters (23.5 feet). Its largest buttresses extend about 6.35 meters (21 feet) from the downstream face and are each roughly 2 meters (7 feet) thick. The buttress spacing varies.

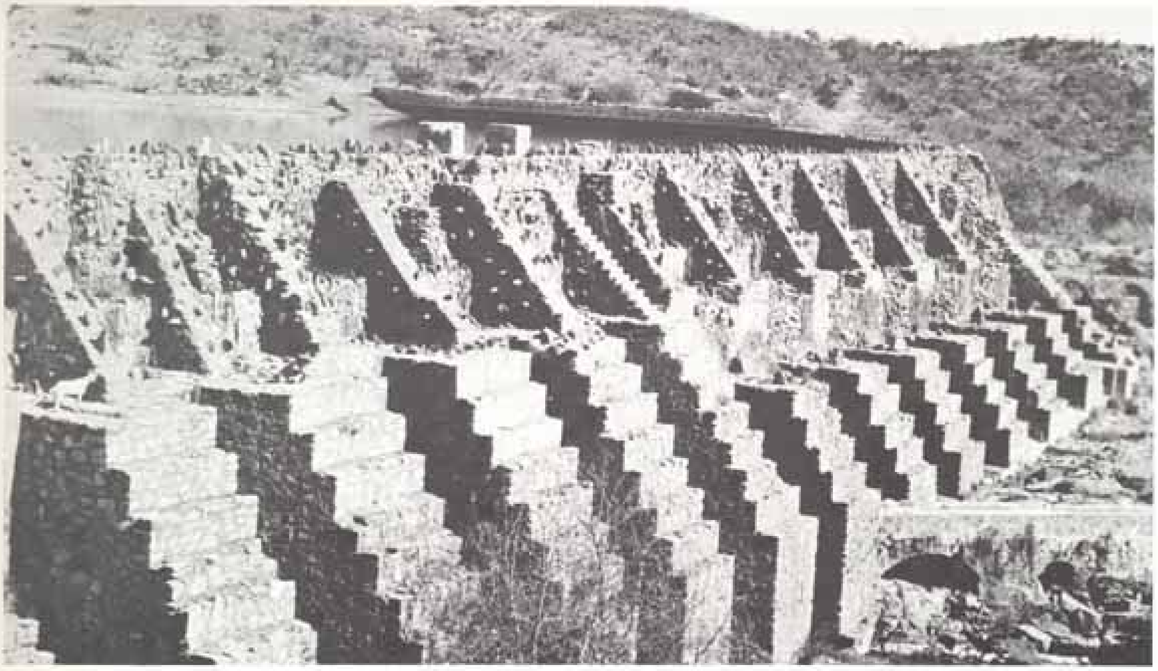


Figure 1-16.—Presa de los Arcos. P-801-D-79302.

The stones in this structure were not dressed, but some of them evidently were squared roughly in the quarrying. In some courses, they were placed on end with staggered joints. The rock is rhyolitic, and the mortar was reportedly made from local hydraulic lime. The noted American engineer Julian Hinds, who wrote about the Aguascalientes dams in the 1930's, was impressed by the remarkable durability of this mortar. He pointed to the example of the Pabell6n Dam's spillway, where many years of spilling had caused only minimal erosion.

Hinds described the local practice of cementing vertical stones in holes dug in the rock to anchor a structure to its foundation. He surmised that this custom had been handed down from earlier generations and that the Pabell6n Dam probably had this feature.

When he visited the site, he found the reservoir silted to a considerable depth. He judged the dam to be overstressed and speculated that the accumulations of sediment may have tended to seal any cracks caused by the overload.

Floods are allowed to pass over the top of the Pabell6n Dam, since the stoplogs in the spillway on the right abutment are apparently left permanently in place. The crest was built several inches lower at the spillway end than in the middle so that small flows discharge there, but during floods the entire right half of the dam serves as a spillway.

Direct overpour is also the method of flood operation at the Presa de los Arcos on the Rio Morcinique, 11 kilometers (7 miles) east of Aguascalientes. The spillway there comprises three small stoplog openings at the right end. However, the logs are reportedly never removed, causing floodwaters to go over the dam.

The Presa de los Arcos **(fig. 1-17)** is a structure about 220 meters (720 feet) long and 20 meters (65 feet) high, with a base thickness of 7.75 meters (25.4 feet). Its buttresses extend 4 meters (13 feet) from the dam base. Stones protruding from the top courses of masonry were presumably to enable an interlocking joint for an additional stage of construction. Several of the buttresses were left uncompleted.

The San Jose de Guadalupe Dam, also on the Rio Morcinique, is a structure with thin, widely spaced buttresses. It was erected in two stages, the original crest having been at the top of the buttresses. The date of first construction is not known precisely, but a tablet on the dam face gives the date of the second stage as 1865. Originally it was about 9 meters (30 feet) high with a vertical upstream face and a stepped downstream face. The height was increased in

1865 to about 11 meters (36 feet). Thickness varies from 0.8 meter (3 feet) at the crest to 2.75 meters (9 feet) at the base. Each of the

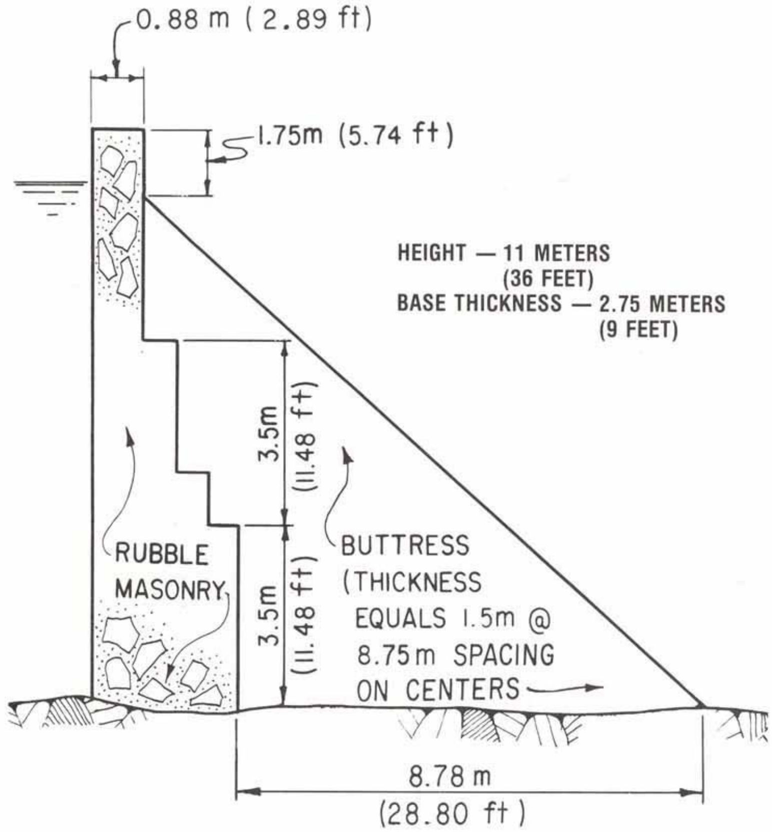


Figure 1-17.—San José de Guadalupe Dam, cross section. P-801-D-79303.

buttresses supporting its downstream face slopes down from the crest of the original dam. Each is 1.5 meters (5 feet) thick. The spacing between centers of buttresses is about 8.75 meters (29 feet). The entire dam is composed of rubble masonry bonded by hydraulic lime mortar.

The river section of the San Jose de Guadalupe Dam is of more massive proportions than the remainder of the structure and has a stoplogged sluiceway extending from foundation to crest. A spillway was built at the right end of the dam, but its stoplogs are left in place during floods. These are removed in the dry season to release water for diversion downstream.

Julian Hinds was amazed that dams of the type seen around Aguascalientes had weathered the centuries and were in such sound condition. Failures had occurred only where basic engineering principles had been conspicuously ignored. Among about fifty such structures with which he was familiar, three failures were known; two of these were attributed to inadequate foundations. He concluded that well-executed work on a good foundation can compensate for many deficiencies in design.

Contemporary with these pioneering achievements in Mexico, the Jesuits introduced dam building to California. One of their first missions received water from the Old Mission Dam **(fig. 1-18)** erected on the San Diego River in 1770. This long barrier, which eventually fell into ruin, was composed of mortared rubble masonry and was about 1.5 meters (5 feet) high.

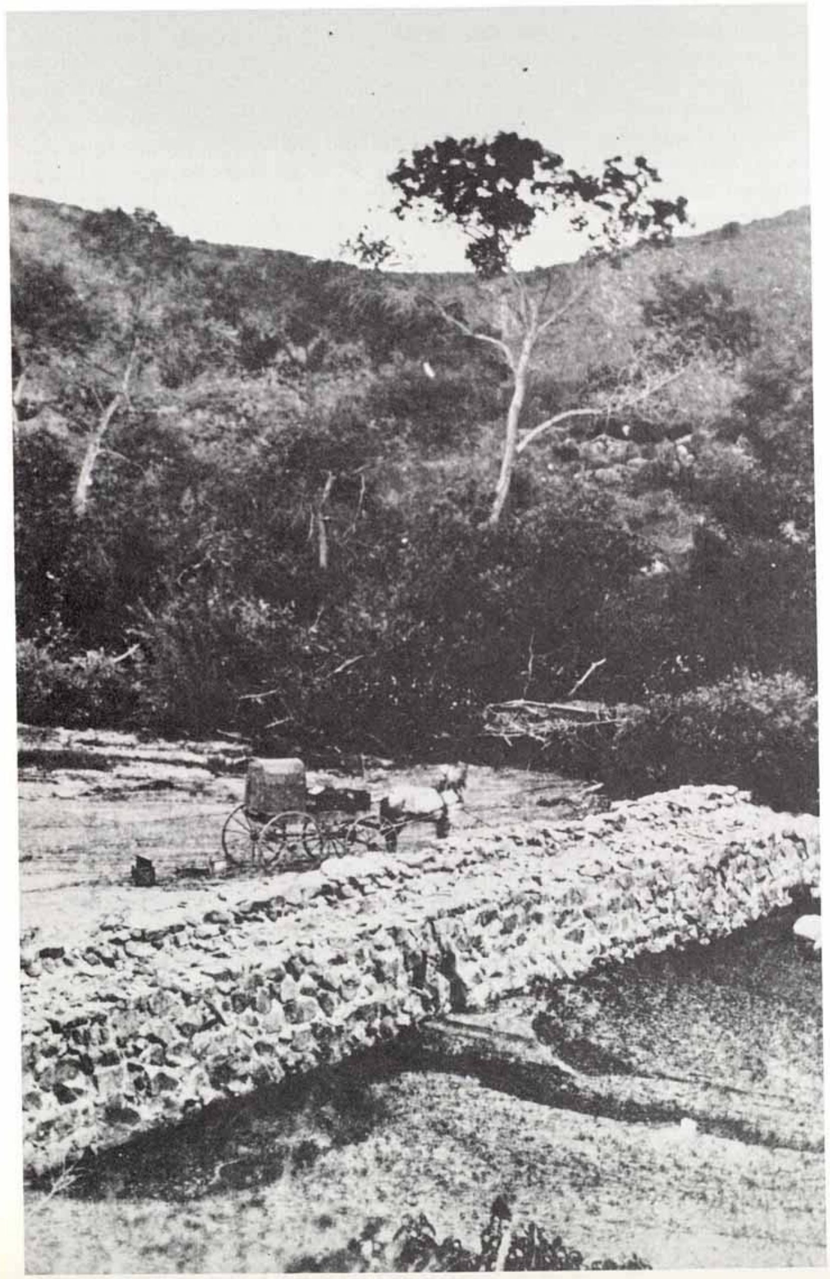


Figure 1-18.—Old Mission Dam (San Diego). P-801-D-79304.

Until the middle of the 19th century, few rational criteria for dam design had any acceptance. Problems encountered in construction were attacked by trial and sometimes by error. The failure of the Puentes Dam **(fig. 1-19**) on the Rio Guadalentin in Spain in 1802 illustrated the weakness of some empirical methods. This 50-meter (164-foot) high rubble-masonry gravity dam was intended to be built on rock, but discovery of a deep crevice in the channel foundation led to use of piling in the alluvial fill under the central part of the structure. Inevitably, after 11 years of service, the inadequate underpinning blew out under reservoir pressure. A new dam was constructed just downstream of this location in 1884.

Another of Spain's 18th century projects was the Valdeinfierno Dam **(fig. 1-20)**, which set a new record for masonry mass in that country. This dam impounded water for the environs of Lorca in the province of Murcia. The dam was built 14 kilometers (9 miles) upstream from the Puentes site, in the canyon of the Rio Luchena, a tributary of the Rio Guadalentin. It was about 35.5 meters (116 feet) high and 87 meters (285 feet) long in a series of seven chords arching upstream (virtually circular). Structural thickness was 12.5 meters (41 feet) at the crest, increasing abruptly at an elevation 4.5 meters (15 feet) under the crest level to about 30 meters (98 feet), and then varying to about 42 meters (137 feet) at the dam base. The reservoir eventually became filled with silt.

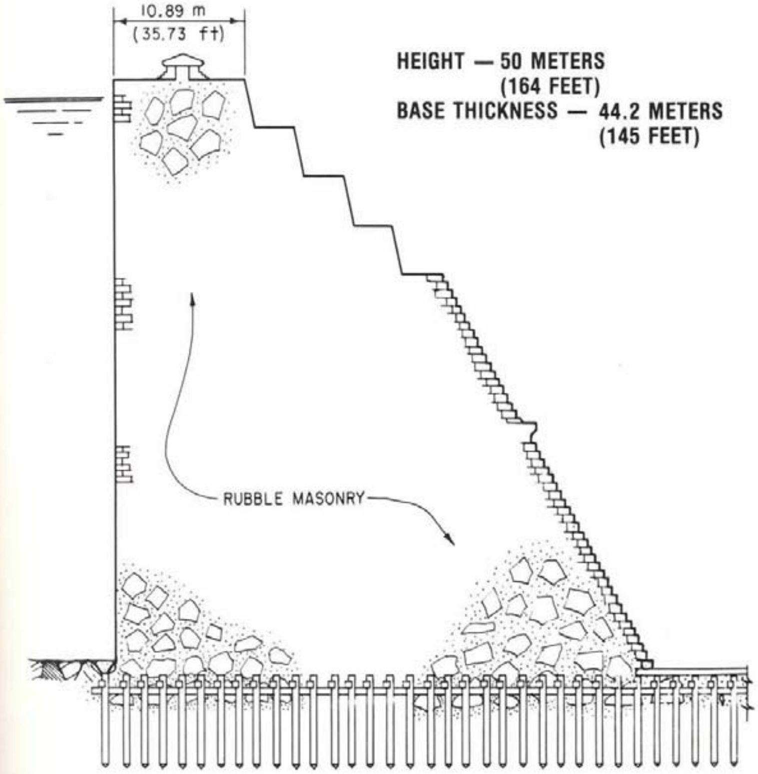
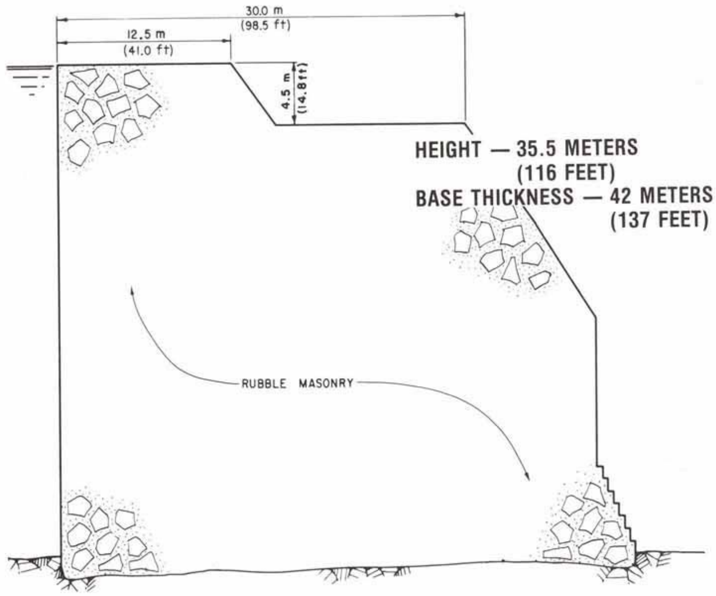


Figure 1-19.—Puentes Dam, cross section. P-801-D-79305.



ORIGINAL DAM AS CONSTRUCTED—1791

Figure 1-20.—Valdeinfierno Dam, cross section. P-801-D-79306.

The Nineteenth Century

The first true multiple-arch water barrier recorded is the Meer Allum Dam, built in about 1800 near Hyderabad in India. This mortared masonry structure is about 12 meters (40 feet) high and measures approximately 762 meters (2500 feet) along its curved axis. Arch thickness is 2.6 meters (8.5 feet). The spans of the 21 vertical arches vary up to a maximum of 45 meters (147 feet). Each buttress is 7.3 meters (24 feet) thick and 12.8 meters (42 feet) long. Although a spillway was provided, some flood flow passes over the crest of the arches. The dam has endured this without detriment.

In 1811, the Couzon Dam was completed near St. Etienne in France. It is a masonry-walled embankment patterned after the St. Ferreol Dam. The masonry core is 33 meters (108 feet) high and 218 meters (715 feet) long, with thickness varying from 4.9 meters (16 feet) at the top to a little more than 6.8 meters (22 feet) at the base. The upstream retaining wall is 10.7 meters (35 feet) high. The one at the downstream face is essentially a low toe block about 5.2 meters (17 feet) thick. Since its rehabilitation in 1896 to control seepage and sliding, the Couzon Dam has remained in service without trouble.

One of the largest of several old dams serving Istanbul, Turkey, is Yeni Dam (also known as the Sultan Mahmut Dam), built in 1839 by the decree of Sultan Mahmut II. This curved masonry gravity structure is 16 meters (52 feet) high and 93 meters (305 feet) long, with a crest thickness of 7 meters (23 feet) and a base thickness of 9.5 meters (31 feet). At the left abutment is a spillway about 1 meter (3 feet) long and 0.5 meter (1.5 feet) high.

During the 19th century, the art of masonry dam construction made important advances. European gravity dams developed architectural form and finish quite in contrast to their crude predecessors. French dam design began to incorporate rational approaches to analysis of forces. In 1853, M. de Sazilly, a French engineer, advocated that pressures within a dam be held to specific limits and that the structure be dimensioned to preclude sliding. However, he did not recognize the concept of keeping the resultant of forces within the middle third of each horizontal plane. This was emphasized about 25 years later by W. J. M. Rankine of England, who also sought a relationship between pressures on different planes in the structure. Lacking a mathematical solution, he suggested assuming different allowable unit pressures for the upstream and downstream faces. The ideas of M. de Sazilly and Rankine showed the way toward logical analysis of dams.

At about the same time, engineers in the eastern part of the United States of America were starting to build some notable dams. Among them were the Old Croton Dam, completed in 1842, on the Croton River for water supply to New York City; Mill River Dam in 1862 for New Haven, Connecticut; Lake Cochituate Dam in 1863 for Boston, Massachusetts; and the Druid Lake Dam in 1871 for Baltimore, Maryland.

During the development of irrigation in the arid western United States, starting in about 1850, many earth dams as high as 38 meters (125 feet) were built, but the number of failures was alarming. Mining also gave impetus to dam building. Discovery of gold in California in 1848 led to extensive placer workings which necessitated the use of dams and conduits. At first, the reservoirs for hydraulic mining were created with stone-filled log cribs. A later development was the dumped rockfill confined by dry rock walls at the faces and lined with two or more layers of wood planking.

Prior to 1850, many small American dams had been fabricated of wood by skilled millwrights. These dams led to the timber crib filled with rock and faced with planking. Such methods were admittedly primitive, but they made effective use of local materials in a land where transportation was difficult.

While these relatively crude works were being constructed by the western I American pioneers, European engineers were engaged in more sophisticated projects. In France, the Zola Dam **(figs. 1-21 and 1-22)** regarded as the first arch dam built by the French, was completed in 1854, with the unprecedented arch height of 42 meters (138 feet). This rubble-masonry structure has cut-stone faces which are still intact. Its crest is curved to a mean radius of 51 meters (168 feet) and is 6 meters (20 feet) thick. At the base, the thickness of the arch is approximately 13 meters (43 feet). The total length of the structure is 66 meters (216 feet).

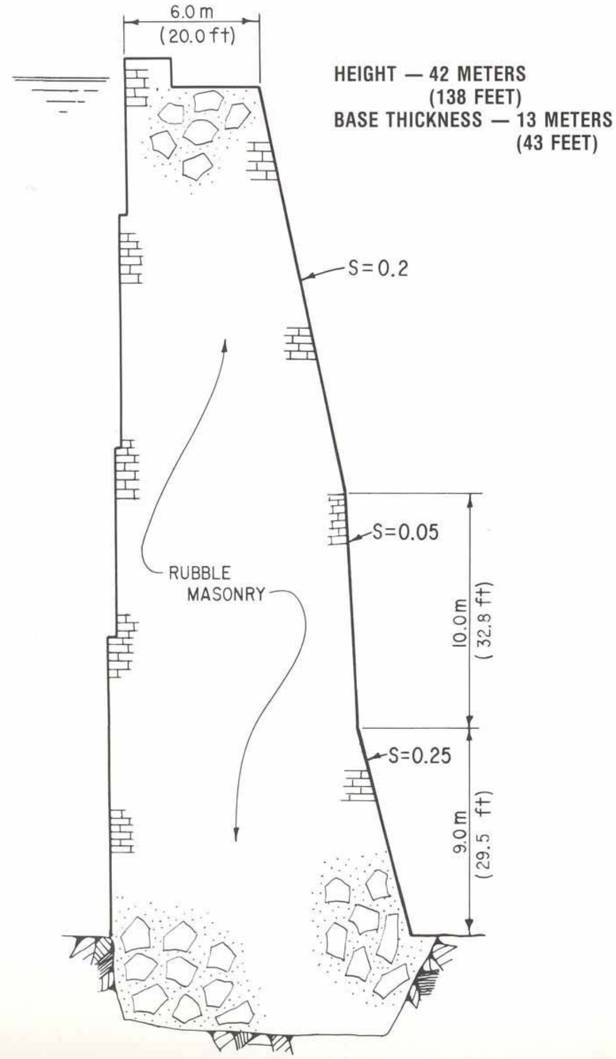


Figure 1-21.—Zola Dam, cross section. P-801-D-79307.

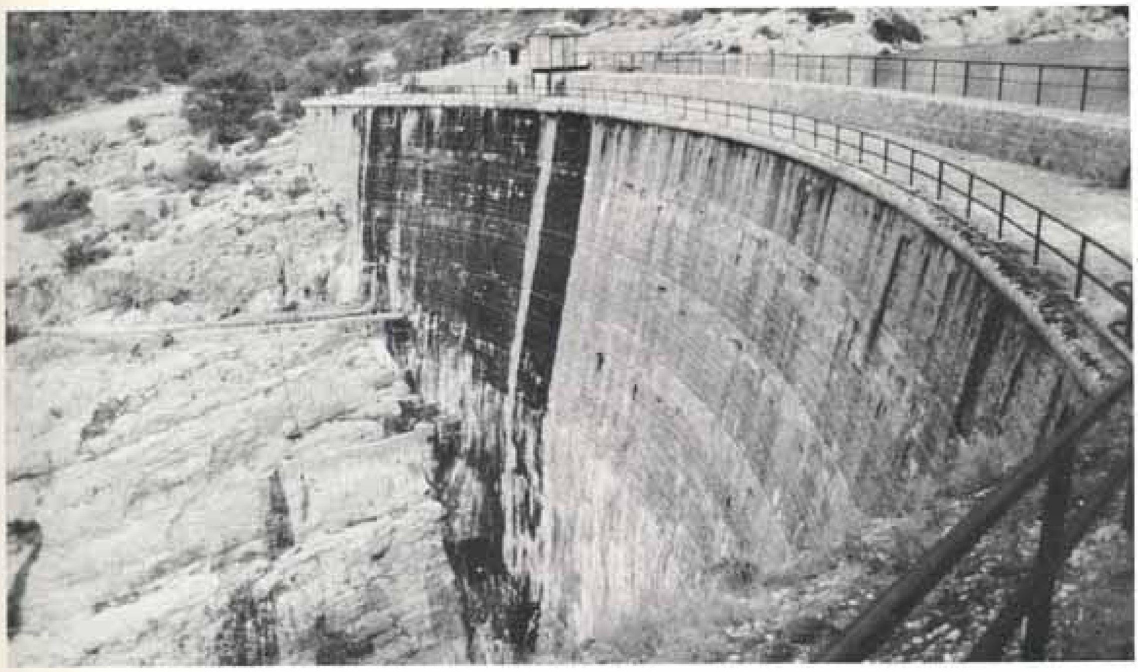


Figure 1-22.—Zola Dam (Courtesy, Comité Français des Grands Barrages, ICOLD). P-801-D-79308.

Also in France, the Gouffre d 'Enfer Dam **(fig. 1-23)** on Le Furan River was completed in 1866 to a height of 60 meters (197 feet). The crest of this rubble-masonry gravity dam is 100 meters (328 feet) long and is curved to a radius of about 252 meters (828 feet). Structural thickness varies from 5 meters (16.4 feet) at the top to 49 meters (161 feet) at the base. The dam continues to provide water to St. Etienne.

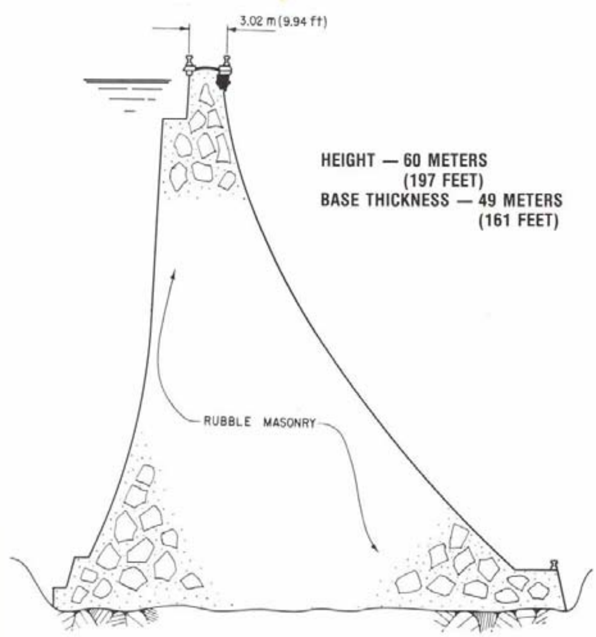


Figure 1-23.—Gouffre d'Enfer Dam, cross section. P-801-D-79309.

The French also constructed several large dams in Algeria. One of the earliest was El Habra Dam **(fig. 1-24),** completed in 1873. Failure of El Habra Dam in 1881 stimulated intensive study of tensile and shear stresses in gravity dams.

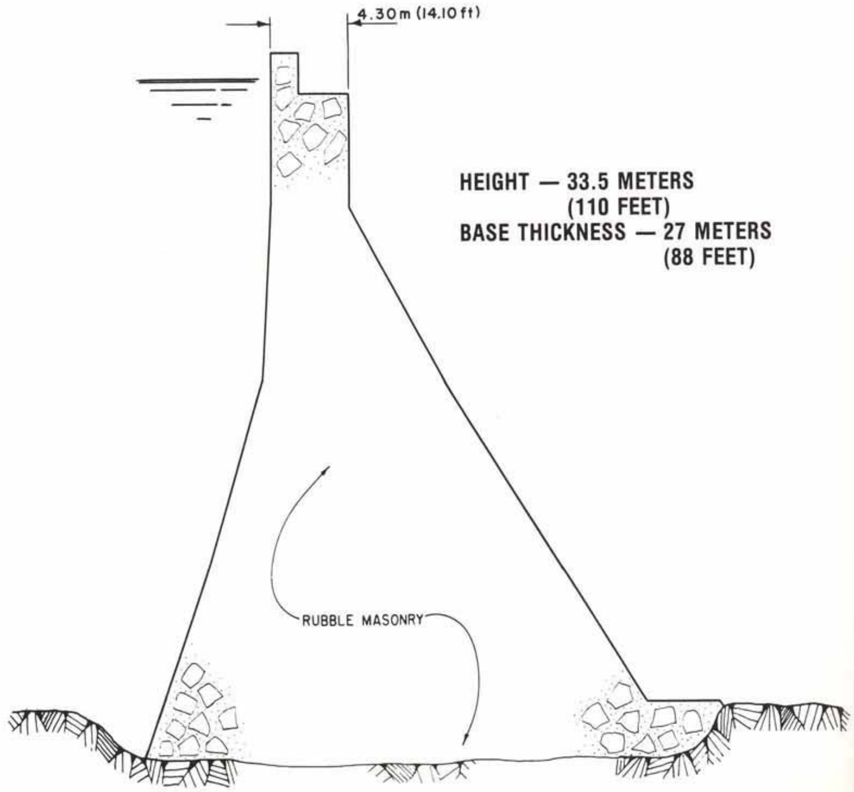


Figure 1-24.—El Habra Dam, cross section. P-801-D-79310.

Meanwhile, the Mutha Canal project in India (1869-79) included some record-breaking masonry dams. Outstanding among these were the Poona Dam **(fig. 1-25),** 40 meters (131 feet) high, and the Bhatgarh Dam, 38.7 meters (127 feet) high and 1.6 kilometers (I mile) long. In 1892, the Tansa Dam was completed to serve Bombay. The dimensions include a length of 2.8 kilometers (1.74 miles) and a height of 41 meters (134 feet). Another Indian structure, the Periyar Dam (1887-97) was built to a height of 54 meters (177 feet). It is a gravity dam **(fig. 1-26)** containing about 141 000 cubic meters (184 000 cubic yards) of concrete made of hydraulic lime, sand, and broken stone. Both faces were built of uncoursed rubble masonry.

In 1875, the first stage of the Lower San Leandro (Chabot) Dam was completed to serve the communities on the east side of San Francisco Bay in California. It was built by Anthony Chabot, who had engineered San Francisco's first public water supply. A special feature of this earthfill structure is a central foundation trench excavated 9 meters (30 feet) below the streambed. In the bottom of the trench, three parallel concrete cutoff walls were built, each 0.9 meter (3 feet) thick and 1.5 meters (5 feet) high, with about half this height anchored in the foundation and half protruding. The fill contains a core zone which is about 27 meters (90 feet) wide at its bottom in the foundation trench. The slopes of the primary original embankment are 3 to 1 upstream and 2Yz to 1 downstream. Within these limits the earth material was dumped by wagons and then sprinkled. Compaction was accomplished by the wagon wheels and by a band of horses which were led back and forth on the fill. A sluiced zone of earth and rock was placed against the 2 Yz to 1 slope on the downstream side, which provided a final outer slope of 6.7 to 1.

Reportedly, more than 800 Chinese workmen were employed in the sluicing operation. When completed in 1875, the

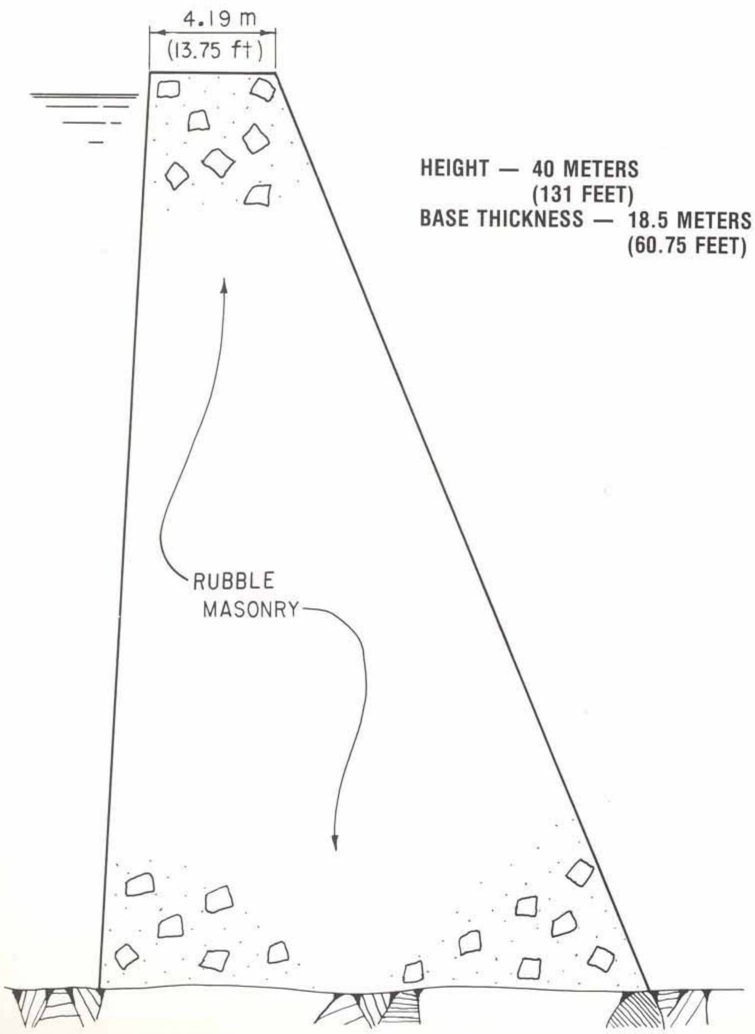


Figure 1-25.—Khadakwasla (Poona) Dam, cross section. P-801-D-79311.

dam rose 35 meters (115 feet) above the streambed and contained a total of approximately 415 000 cubic meters (543 000 cubic yards), of which about 30 percent was sluiced. The dam was enlarged in the 1890's and its height above foundation is now recorded as 47 meters (154 feet) and its length as 137 meters (450 feet).

The Twentieth Century

In Egypt, the Aswan Dam **(fig. 1-27)** was completed in 1902 on the mainstream of the Nile. The quarried-granite mass was 20 meters (65.5 feet) high and 1951 meters (6400 feet) long. Enlargement of this gravity dam to a height of 27 meters (88.5 feet) was completed in 1912, followed by a further increase in 1933. Its height above foundation is now 53 meters (174 feet). Successful operation of the Aswan storage facility was attributable in part to provision of sluiceways in the structure which allowed silt to flow through to the irrigated lands of the *lower* Nile.

In the United States, early gravity dams generally had conservative proportions. Cheesman Dam **(fig. 1-28),** completed in Colorado in 1904, was 72 meters (236 feet) in height and curved in plan on a radius of 122 meters (400 feet) even though it was a full gravity section. This established an American precedent for the arch-gravity barrier. Engineers recognized that the joints in these structures should be filled so as to resist loads. Otherwise the arch function could not develop until deflection under gravity action had closed the joints.

Design concepts for gravity dams were beginning to change. The middle third criterion for dimensioning these structures was being questioned. It had been generally accepted as assurance against overturning of moderately loaded dams. But several failures demonstrated that uplift and sliding could be of greater concern. Designers began to consider these factors in engineering new projects.

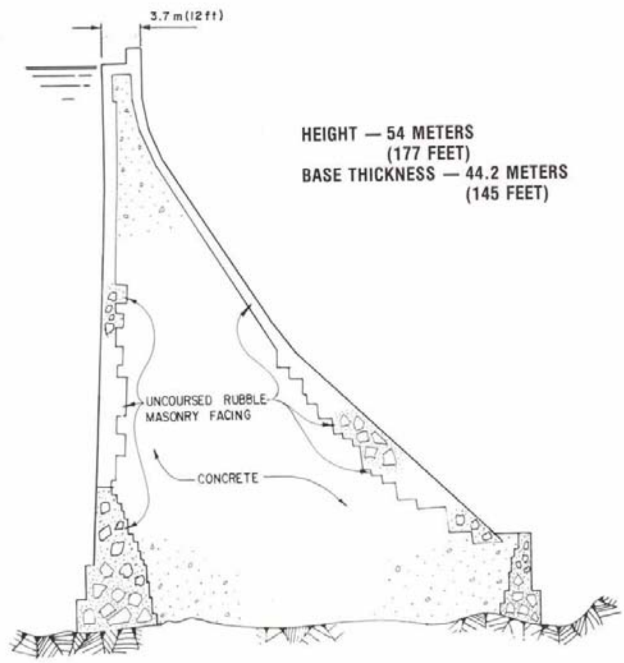
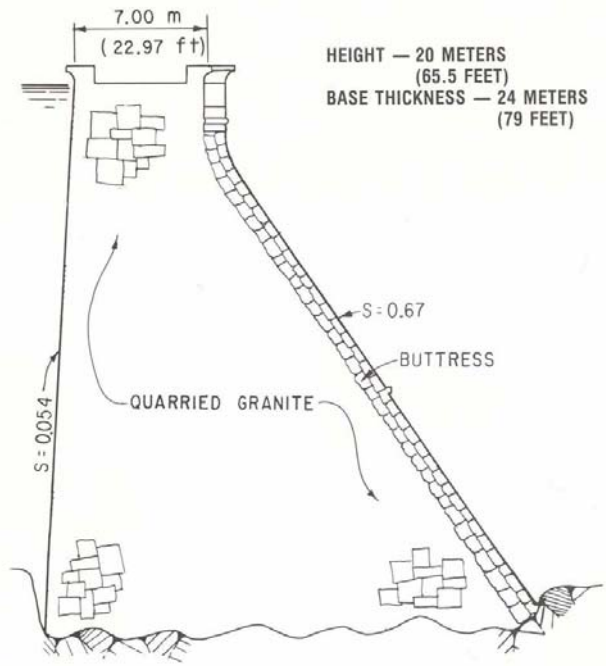


Figure 1-26.—Periyar Dam, cross section. P-801-D-79312.



ORIGINAL DAM AS CONSTRUCTED—1902

Figure 1-27.—Aswan Dam, cross section. P-801-D-79313.

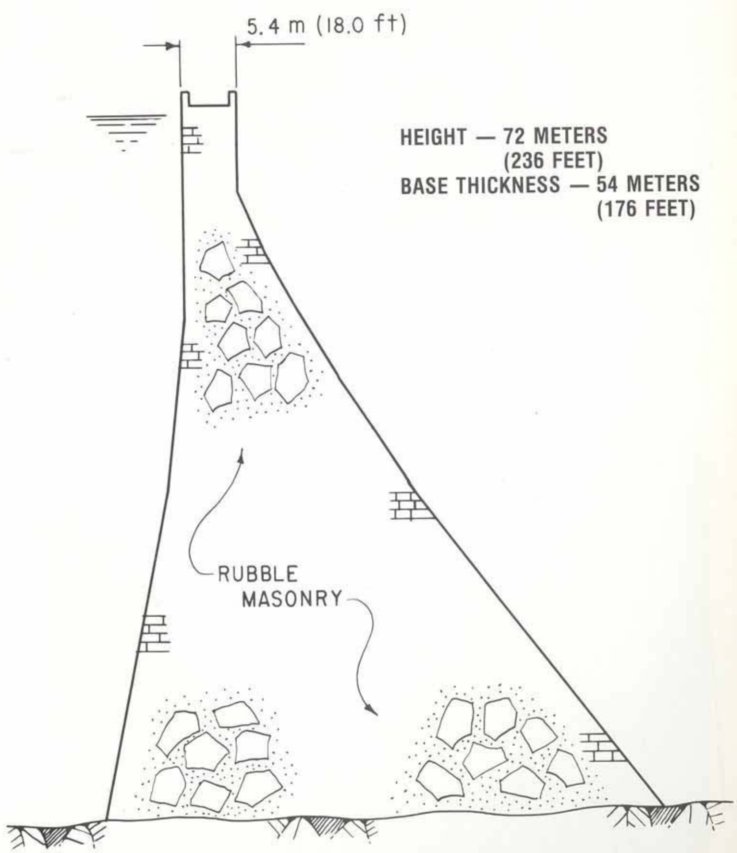


Figure 1-28.—Cheesman Dam, cross section. P-801-D-79314.

As early as 1882, a drain network to reduce uplift had been incorporated into the design of the Vyrnwy Dam **(figs. 1-29 and 1-30)** for the water system of Liverpool, England. Engineers in the United States gave first recognition to uplift in design of the Wachusetts Dam in Massachusetts (1900-1906). A *cutoff* was built under the dam downstream from its heel, but no drains were provided. Olive Bridge Dam in New York State (1908-14) was constructed with drains in the structure *itself* but with none in the foundation. Among the first dams with both masonry and rock drainage were Medina in Texas (1911-12), Arrowrock in Idaho (1914-15), and Elephant Butte in New Mexico (1914-15). The foundations at these sites were drilled to control seepage. Since then, drilling has been common practice for large gravity dams.

The New Croton Dam **(fig. 1-31),** a gravity structure completed in 1905, was one of the last major American dams of cut-stone masonry. While natural cement was used on this job, it was also one of the first applications of American portland cement. [In later projects portland cement found increasing acceptance, but natural cement was used as a blend with portland cement (up to 25 to 30 percent) in several structures, including Bull Shoals, Clark Hill, Wolf Creek (all built around 1945-50) and the Robert Moses (Barnhart Island) Dam (1959).] New Croton was the highest dam in the world - 90.5 meters (297 feet) above its foundation. However, this new record was soon surpassed.

Within the next few years, three important arched barriers were completed in the West. The 85-meter *(280-foot)* high Theodore Roosevelt Dam (1911), a thick, arch-gravity structure **(figs. 1-32 and 1-33)** in Arizona, and the 65-meter *(214-foot)* high Pathfinder Dam **(fig. 1-34)** (1909) in Wyoming were built of stone masonry. The Buffalo Bill (Shoshone) Dam **(figs. 1-35 and 1-36)** (1910), also in Wyoming, attained a record-setting height of 99 meters (325 feet). Pathfinder and Buffalo Bill **(fig. 1-37)** are true arches.

New precedents were set by the l07-meter (350-foot) high Arrowrock Dam **(fig. 1-38)** on the Boise River in Idaho. In the construction of this concrete, thick, arch-gravity dam, completed in 1915, first use was made of spouted cobble concrete, introducing methods of placement that gained wide acceptance. Although the structure was arched on a radius of 204 meters (670 feet), the conservative section had a maximum base thickness of 68 meters (223 feet). With such mass, it must function primarily as a gravity dam, relying more on its weight than on any arch action.

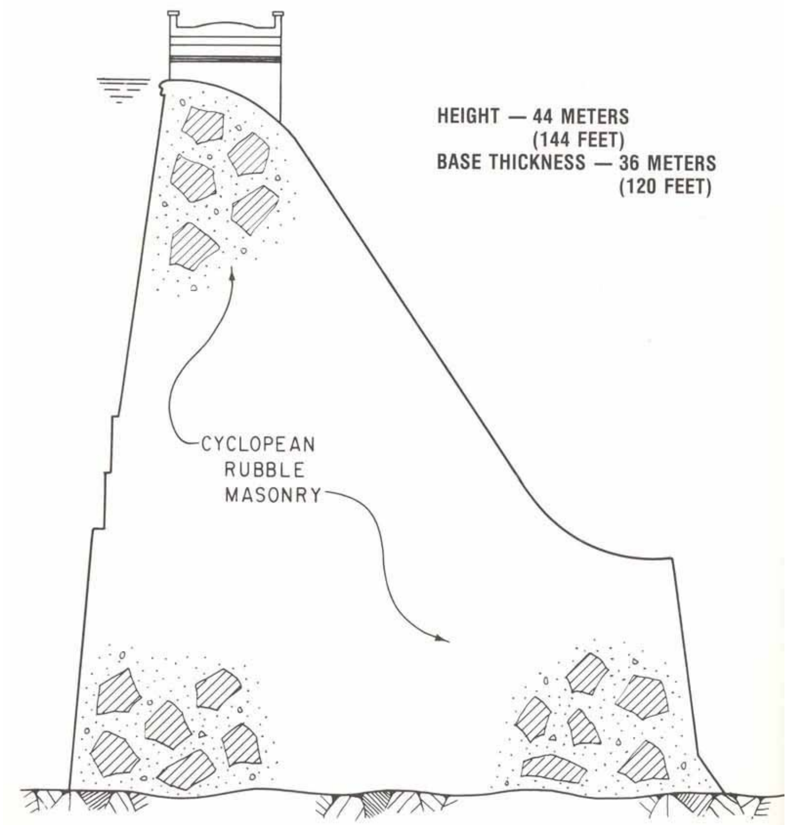


Figure 1-29.—Vyrnwy Dam, cross section. P-801-D-79315.

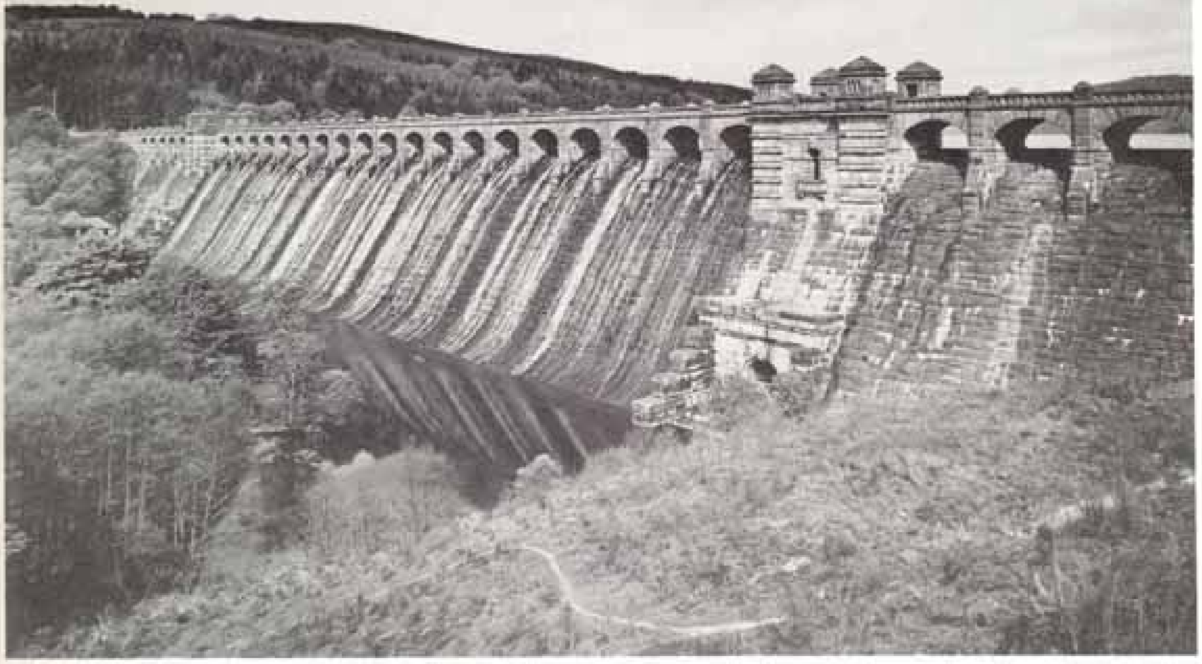


Figure 1-30.—Vyrnwy Dam (Courtesy, British National Committee, ICOLD). P-801-D-79316.

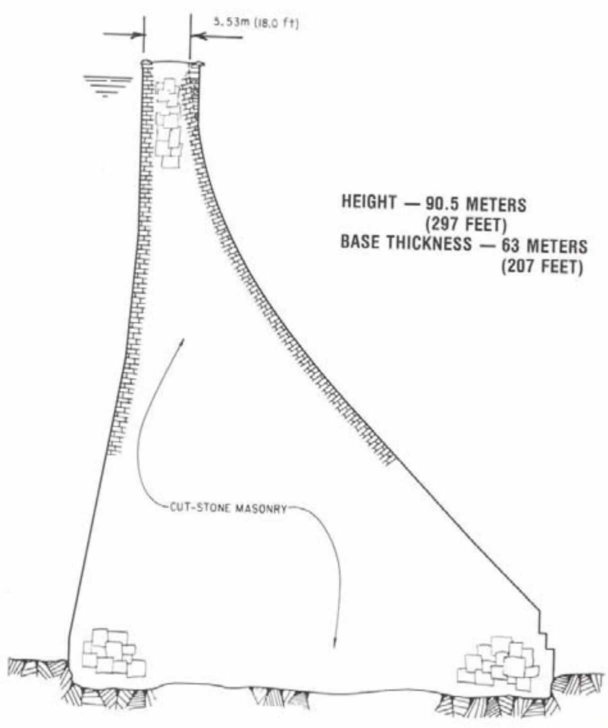


Figure 1-31.—New Croton Dam, cross section. P-801-D-79317.

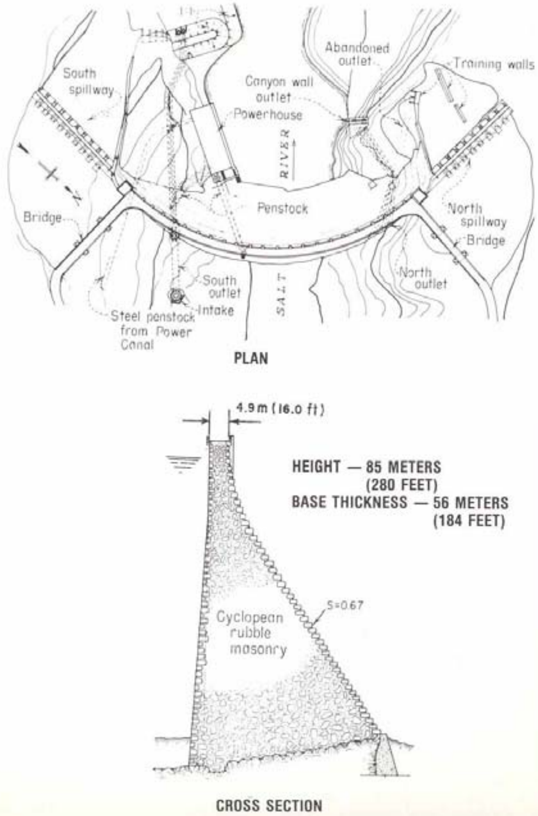


Figure 1-32.—Theodore Roosevelt Dam, plan and cross section. P-801-D-79318.

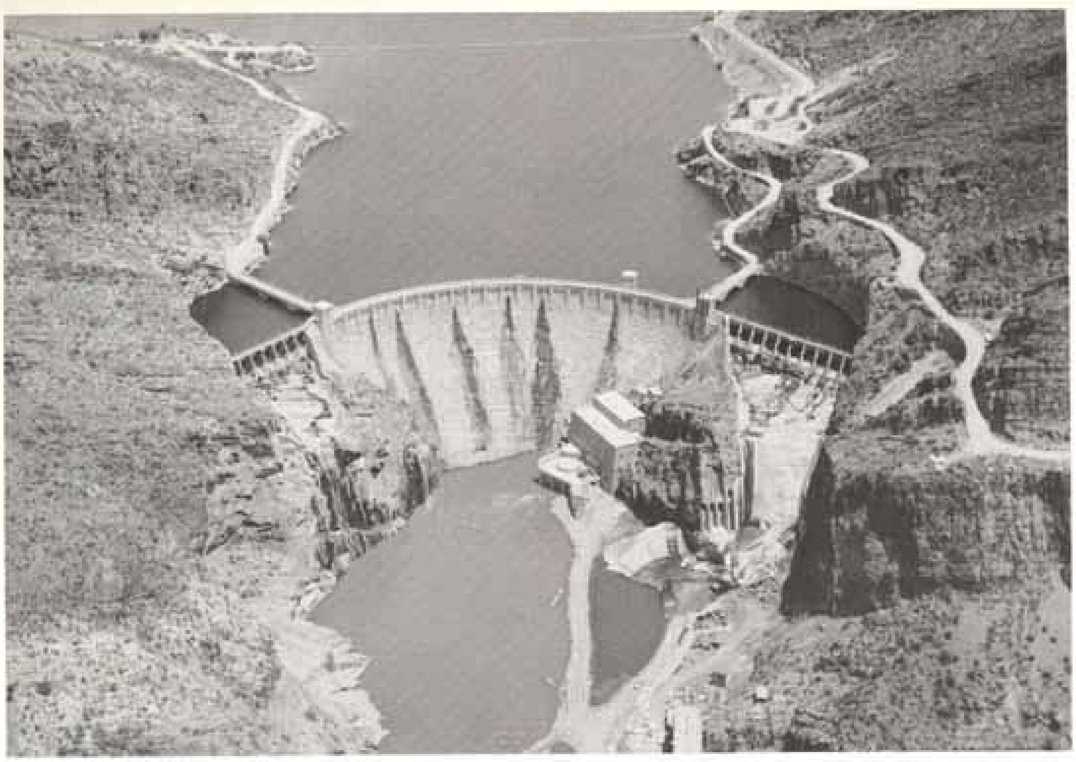


Figure 1-33.—Theodore Roosevelt Dam. P-801-D-79319.

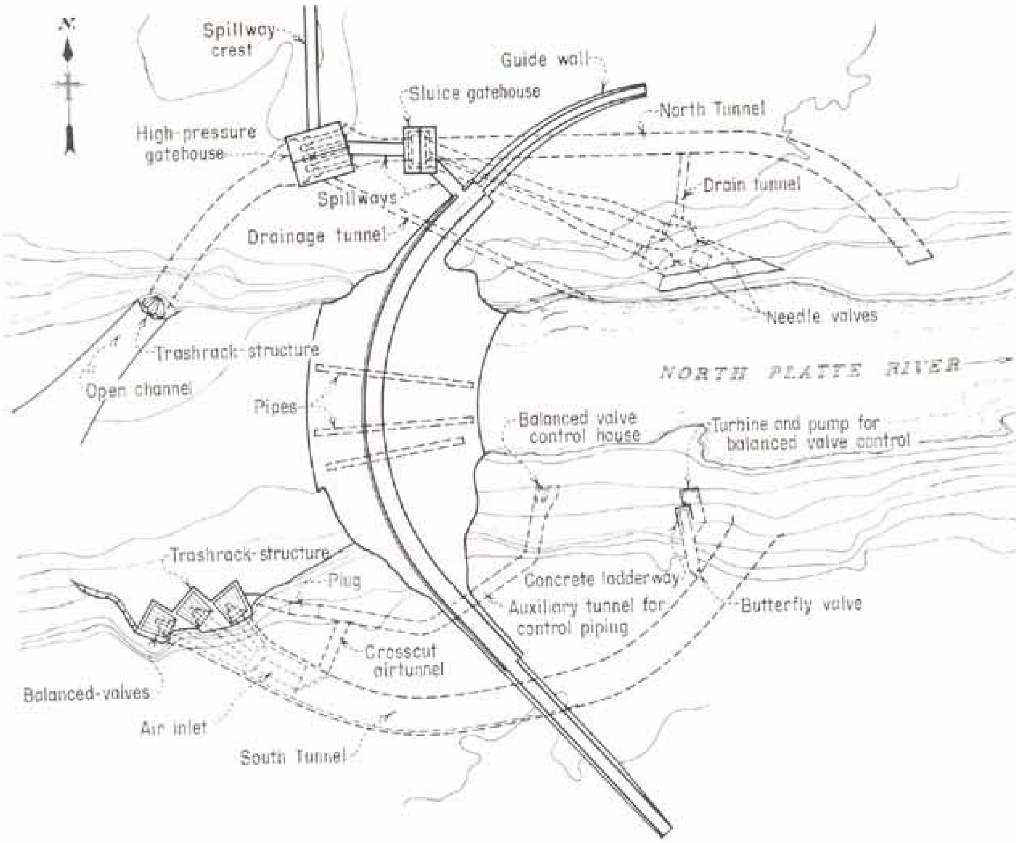


Figure 1-34.—Pathfinder Dam, plan. P-801-D-79320.

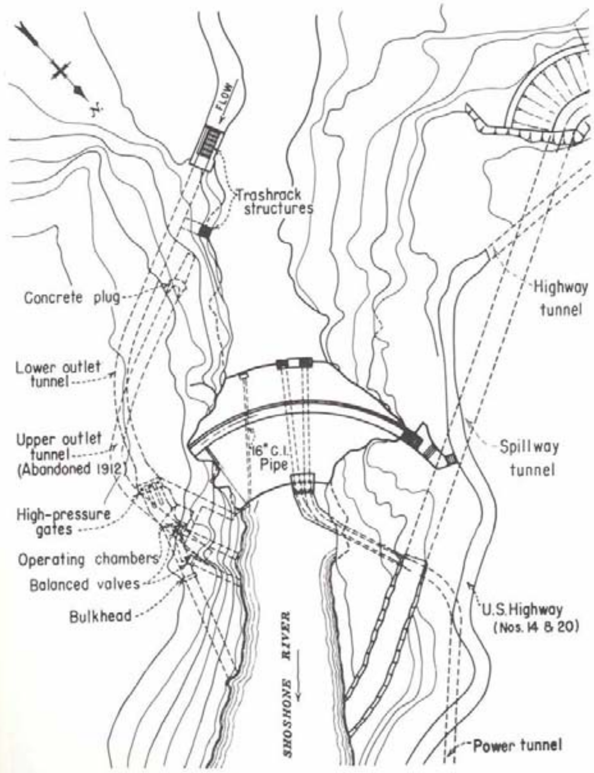


Figure 1-35.—Buffalo Bill (Shoshone) Dam, plan. P-801-D-79321.

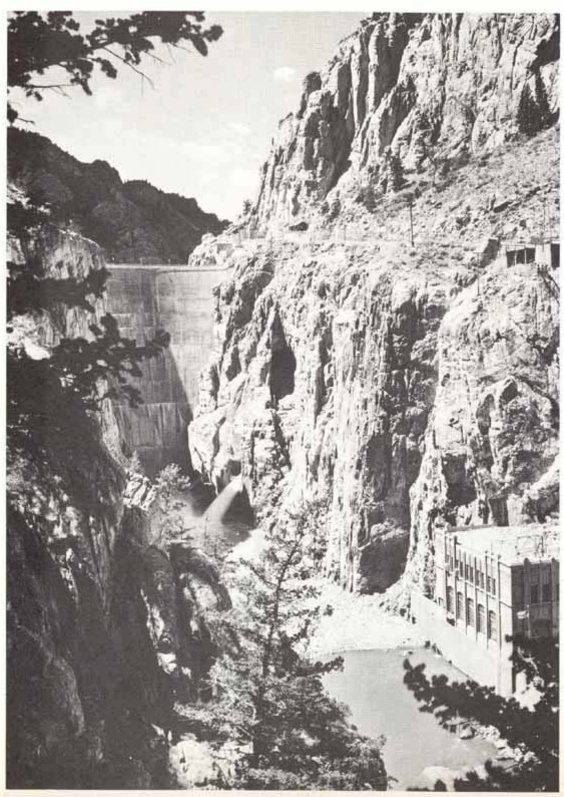


Figure 1-36.—Buffalo Bill (Shoshone) Dam (P26-600-1353A). P-801-D-79322.

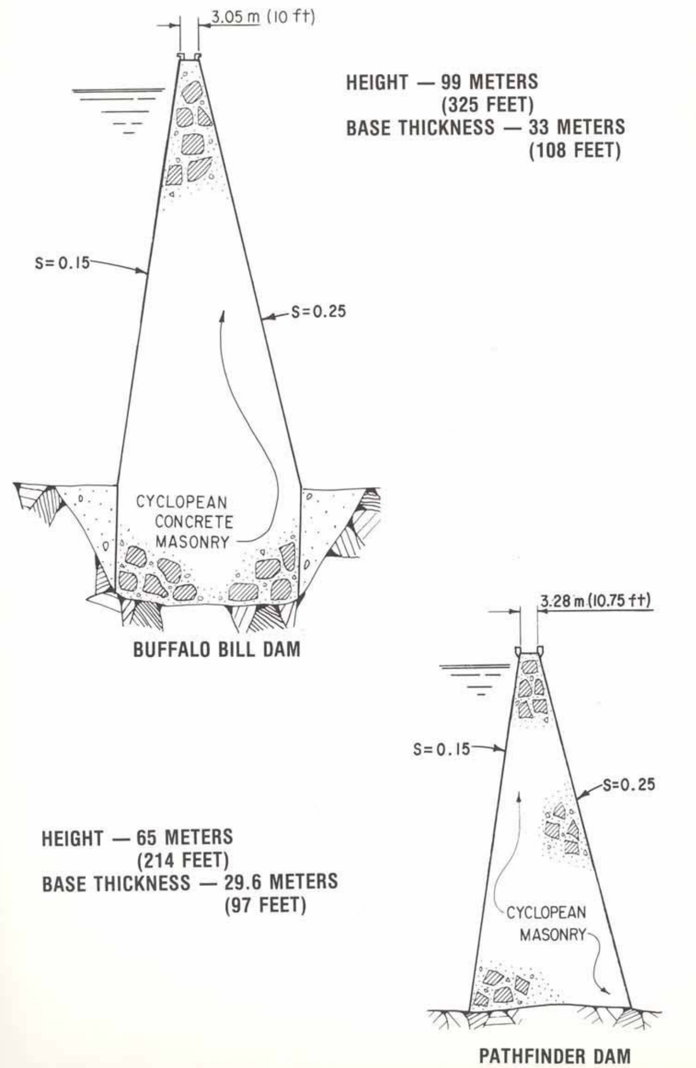


Figure 1-37.—Buffalo Bill (Shoshone) and Pathfinder Dams, cross sections. P-801-D-79323.

Figure 1-38.—Arrowrock Dam (P4-100-851I). P-801-D-79324.

The 94-meter (308-foot) high Kensico Dam, built to provide water storage for the Catskill Aqueduct, introduced a new era in United States dam construction. This straight gravity structure, erected in the period 1910 to 1915, was composed of "cyclopean concrete" produced by highly mechanized methods. Railroad trains transported the cyclopean stones and buckets of concrete to the dam site, where electrically powered derricks hoisted and placed them in the forms. The concrete mass was finally faced with stone masonry.

Americans were also making progress in embankment construction. Some of their first major earth fills were in California, including the 67-meter (220-foot) high San Pablo Dam, completed in 1920, and the Calaveras Dam of the same height, in 1925. In terms of embankment volume, the Saluda Dam (1930) in South Carolina held the United States record of approximately 8,400,000 cubic meters (11,000,000 cubic yards) until the Fort Peck Dam **(fig. 1-39)** (1935-40) in Montana with nearly 96,034,000 cubic meters (125,600,000 cubic yards).

Figure 1-39.—Fort Peck Dam (Courtesy, U.S. Corps of Engineers). P-801-D-79325.

Rockfill dam technology was given new impetus in the United States. In 1924, the Dix River Dam for the water supply of Danville, Kentucky, established a height record of 84 meters (275 feet) for rockfills. It is a combination of embankment and gravity section. In 1931, the Salt Springs Dam in California raised the record to 100 meters (328 feet).

Outstanding concrete arch dams built in the United States during this period include the Pacoima Dam (1929) in California, built for flood control in Los Angeles County, to a record height of 113 meters (370 feet), and the Diablo Dam (1929) in Washington, setting a new mark of 119 meters (390 feet). The Owyhee Dam (1932), a concrete, thick, arch-gravity structure in Oregon **(figs. 1-40 and 1-41),** was designed as an arch. Its crest is 162 meters (530 feet) above the bottom of the cutoff trench. Officially, the height of this dam is listed as 127 meters (417 feet).

Techniques for mixing and placing concrete were undergoing significant changes. The constructors of the Diablo Dam, for example, used a dry mix placed by a belt conveyor suspended from a derrick, with a short tube known as an "elephant trunk" at the discharge end. The recognized disadvantages of segregation and voids in wet, spouted concrete spurred attempts to find methods of placing an even drier mix. In the construction of the Calderwood (Tennessee) and Chute a Caron **(fig. 1-42)** (Quebec, Canada) Dams, completed in 1930, use was made of bottom-dump buckets that enabled placing relatively dry concrete in the forms without segregation. This procedure became widely approved.

Hoover (Boulder) Dam **(fig. 1-43),** built during the period from 1931 to 1936 on the Colorado River, is a massive, thick, arch-gravity structure containing a total of 3,400,000 cubic meters (4,400,000 cubic yards) of concrete. It has a height of 221 meters (726 feet) above the foundation, a crest length of 379 meters (1244 feet), and a thickness varying from 13.7 meters (45 feet) at the top to 201 meters (660 feet) at the base. While this huge dam drew worldwide attention, its mass was soon exceeded by the 8,100,000 cubic meters (10,600,000 cubic yards) of the

Grand Coulee Dam **(fig. 1-44)** (1942) on the Columbia River in Washington, and the 67,005,000 cubic meters (8,700,000 cubic yards) of Shasta Dam **(fig. 1-45)** (1945) on the Sacramento River in California.

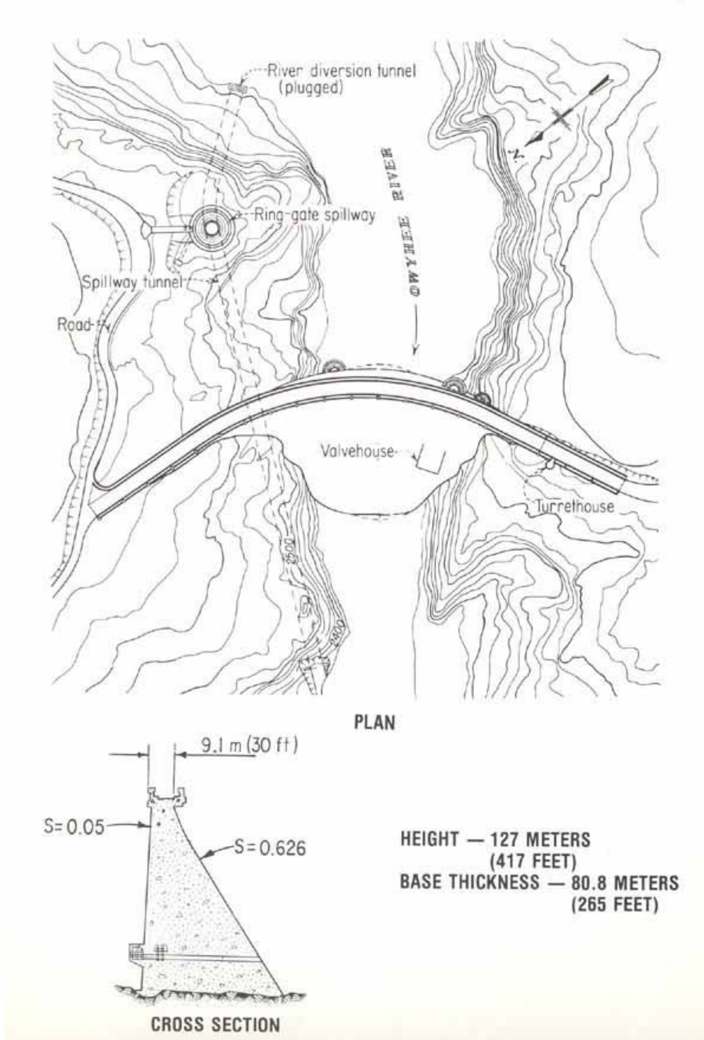


Figure 1-40.—Owyhee Dam, plan and cross section. P-801-D-79326.

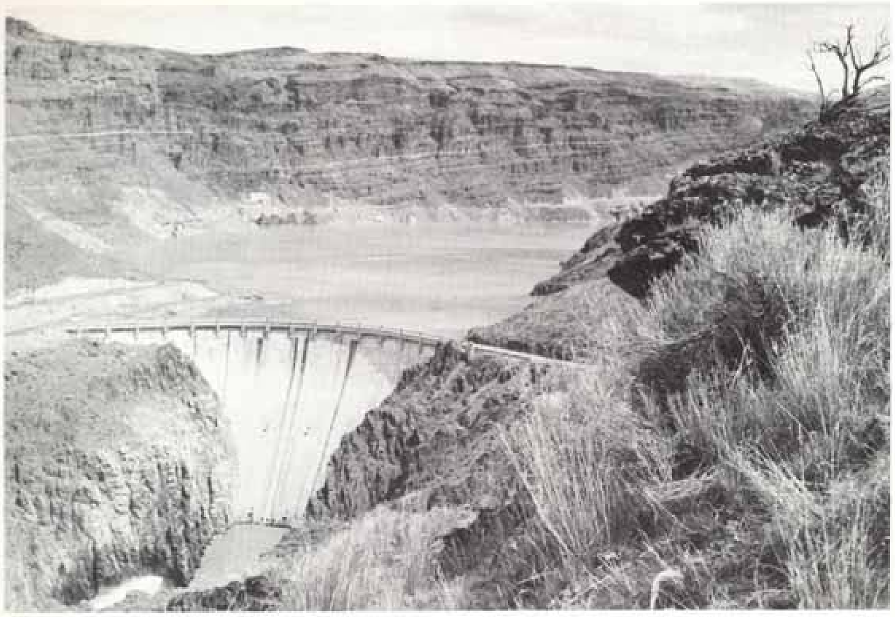


Figure 1-41.—Owyhee Dam (P48-100-4131). P-801-D-79327.

Figure 1-42.—Chute à Caron Dam (Courtesy, Alcan Smelters and Chemicals, LTD). P-801-D-79328.

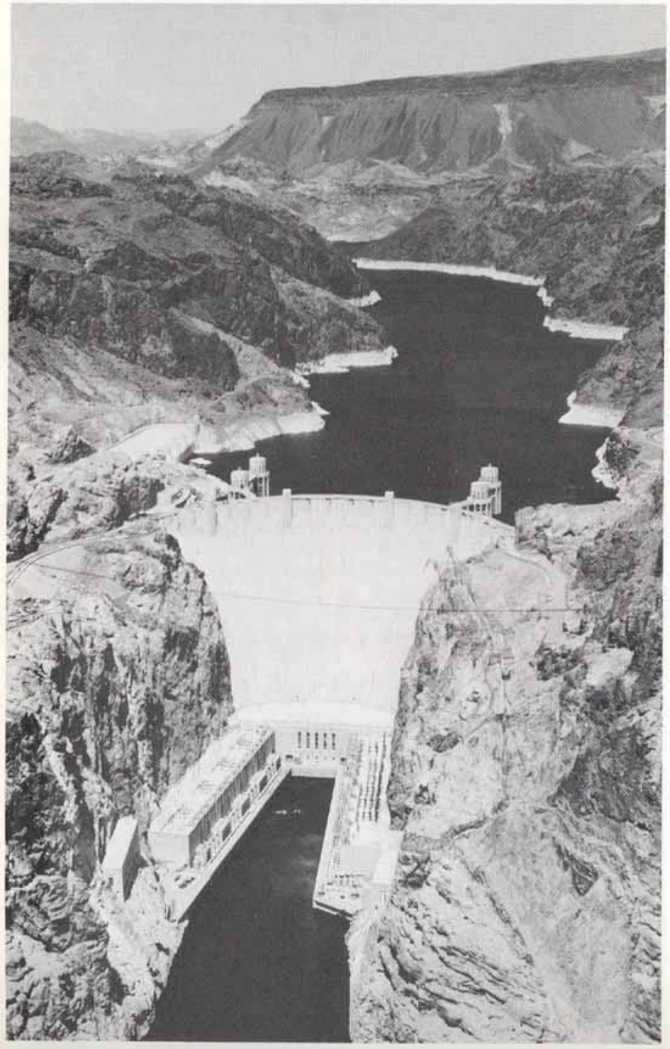


Figure 1-43.—Hoover (Boulder) Dam (P45-300-10769). P-801-D-79329.

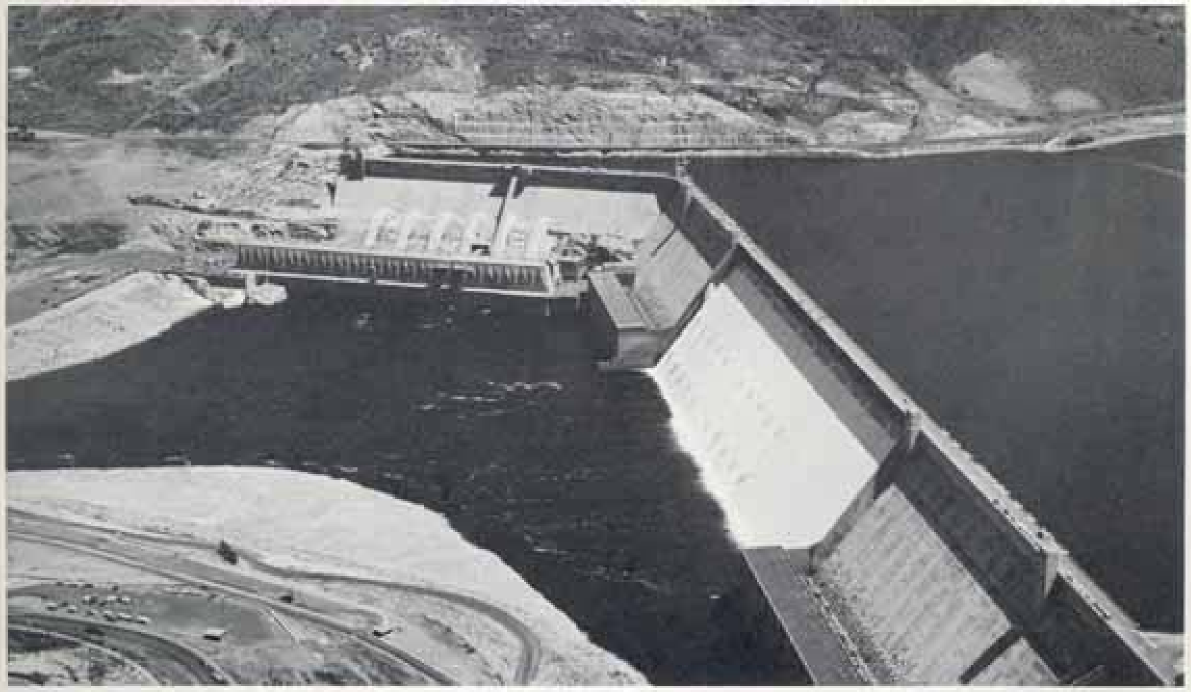


Figure 1-44.—Grand Coulee Dam (P222-117-48654). P-801-D-79330.

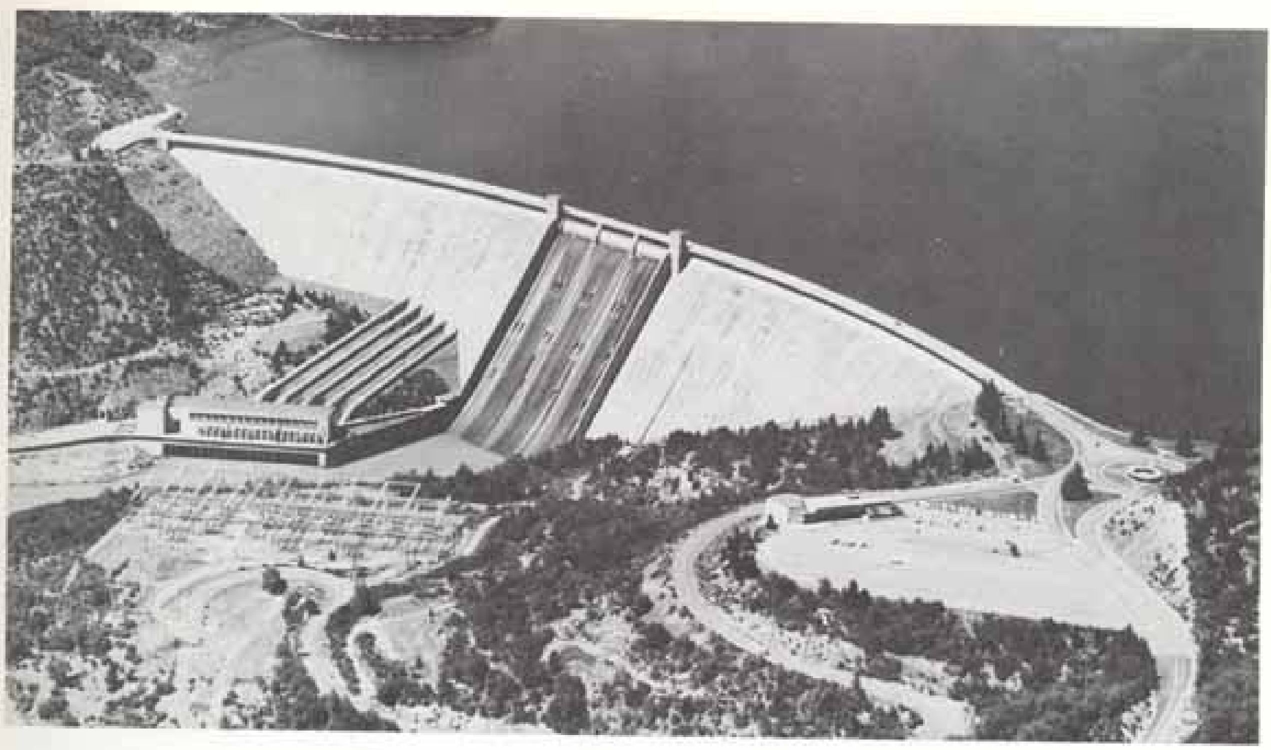


Figure 1-45.—Shasta Dam (P(S)-200-12006NA). P-801-D-79331.

Glen Canyon Dam **(fig. 1-46),** an arched concrete structure, was completed in 1964. It is located on the Colorado River in Arizona and is among the highest in the United States. It is 216 meters (710 feet) high and 475 meters (1560 feet) long. Arch thickness varies from 7.6 meters (25 feet) at the crest to 91.5 meters (300 feet) at the base. The total concrete volume is 3 750 000 cubic meters (4 900 000 cubic yards).

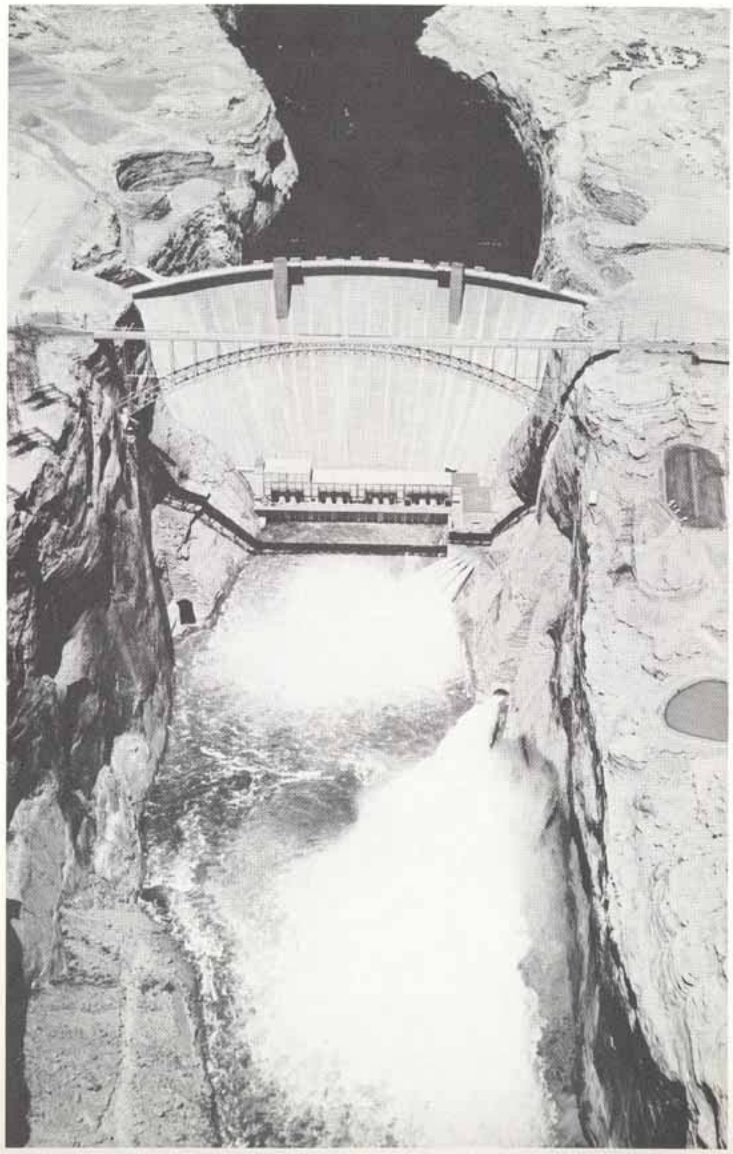


Figure 1-46.—Glen Canyon Dam (P557-400-383). P-801-D-79332.

Dworshak Dam **(fig. 1-47)** on the North Fork of the Clearwater River in Idaho was completed in 1972. It is a straight concrete gravity structure 219 meters (717 feet) high and 1002 meters (3287 feet) long, with a volume of 4 970 000 cubic meters (6 500000 cubic yards).

Oroville Dam **(figs. 1-48 and 1-49*)*** (1967), the primary storage feature of California's State Water Project, is a 235-meter (770-foot) high zoned earthfill structure with a volume of 61,000,000 cubic meters (80,000,000 cubic yards). The selection of the embankment type dam was governed by the abundant supply of ideal pervious materials that had been produced by dredgers mining for gold in the flood plain of the Feather River. Unique laboratory compaction equipment was developed for testing the large-size cobble material used in the dam. These facilities can accommodate an earthrock specimen 914 millimeter (36 inches) in diameter and 2286 millimeters (7.5 feet) high.

Two precedent-setting Canadian structures include the Daniel Johnson (Manicouagan No.5) Dam **(fig. 1-50)** (1968), a multiple arch dam 214 meters (702 feet) high, located in the bush country of Quebec 805 kilometers (500 miles) from Montreal which consists of 13 arches supported by 12 buttresses, with the central arch spanning 161.5 meters (530 feet); and Mica Dam (1973) an earthfill structure located about 128 kilometers (80 miles) north of Revelstoke on the Columbia River. Its height above lowest point of foundation is about 242 meters (794 feet), and it is 792 meters (2598 feet) long.

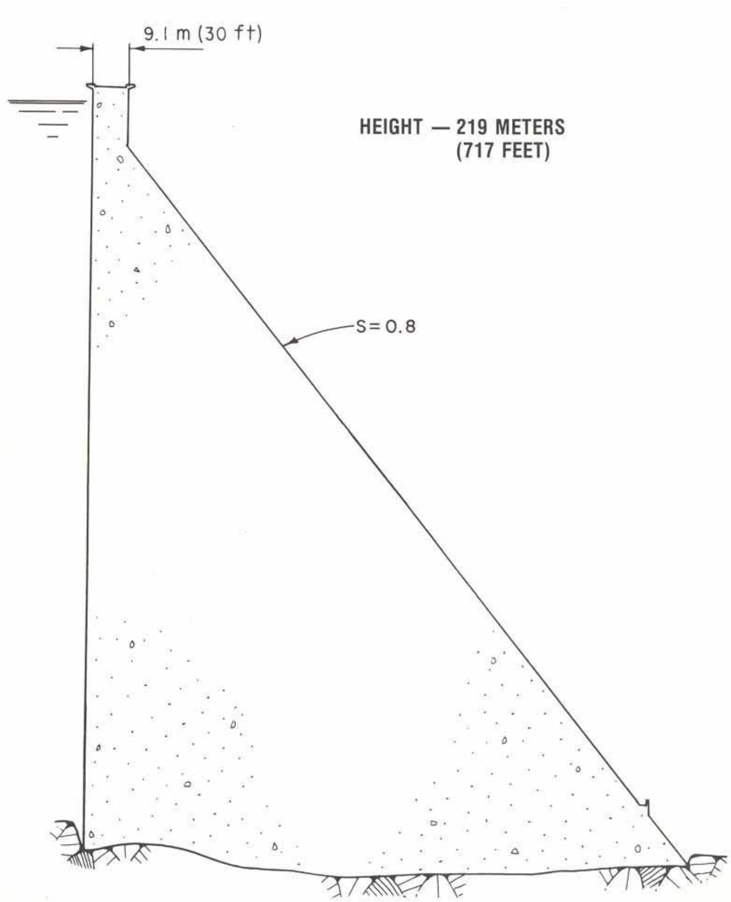


Figure 1-47.—Dworshak Dam, cross section. P-801-D-79333.

Figure 1-48.—Oroville Dam (Courtesy, Calif. Dept. of Water Resources). P-801-D-79334.

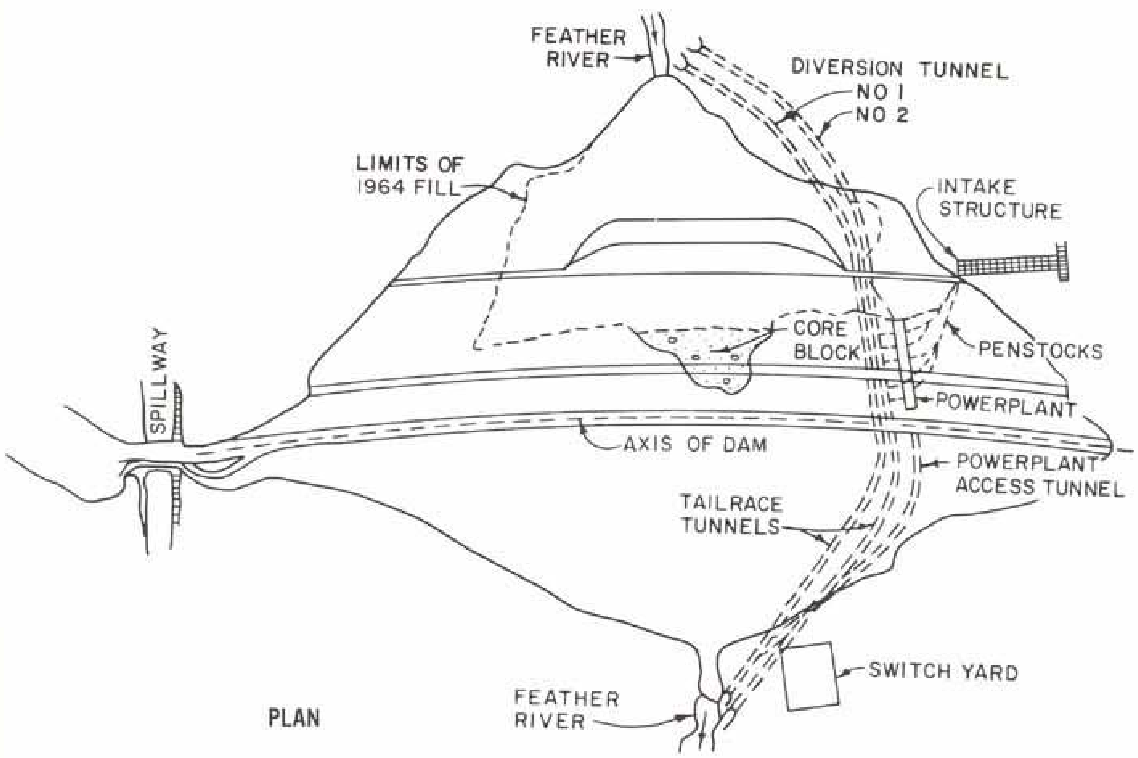


Figure 1-49.—Oroville Dam, plan and cross section (1 of 2). P-801-D-79335.

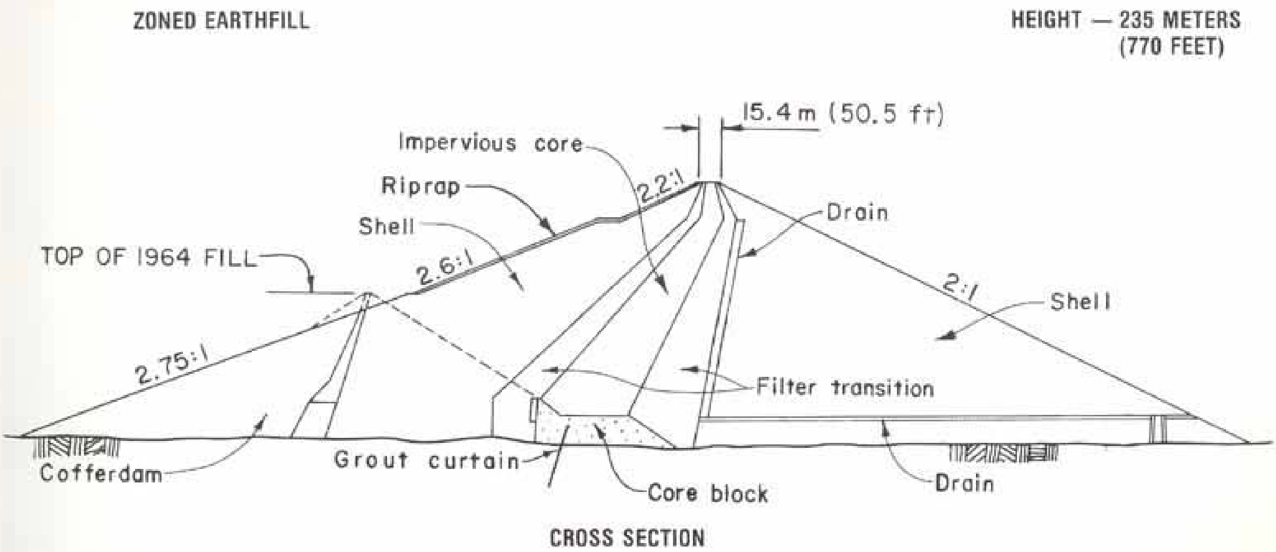


Figure 1-49.—Oroville Dam, plan and cross section (2 of 2). P-801-D-79336.

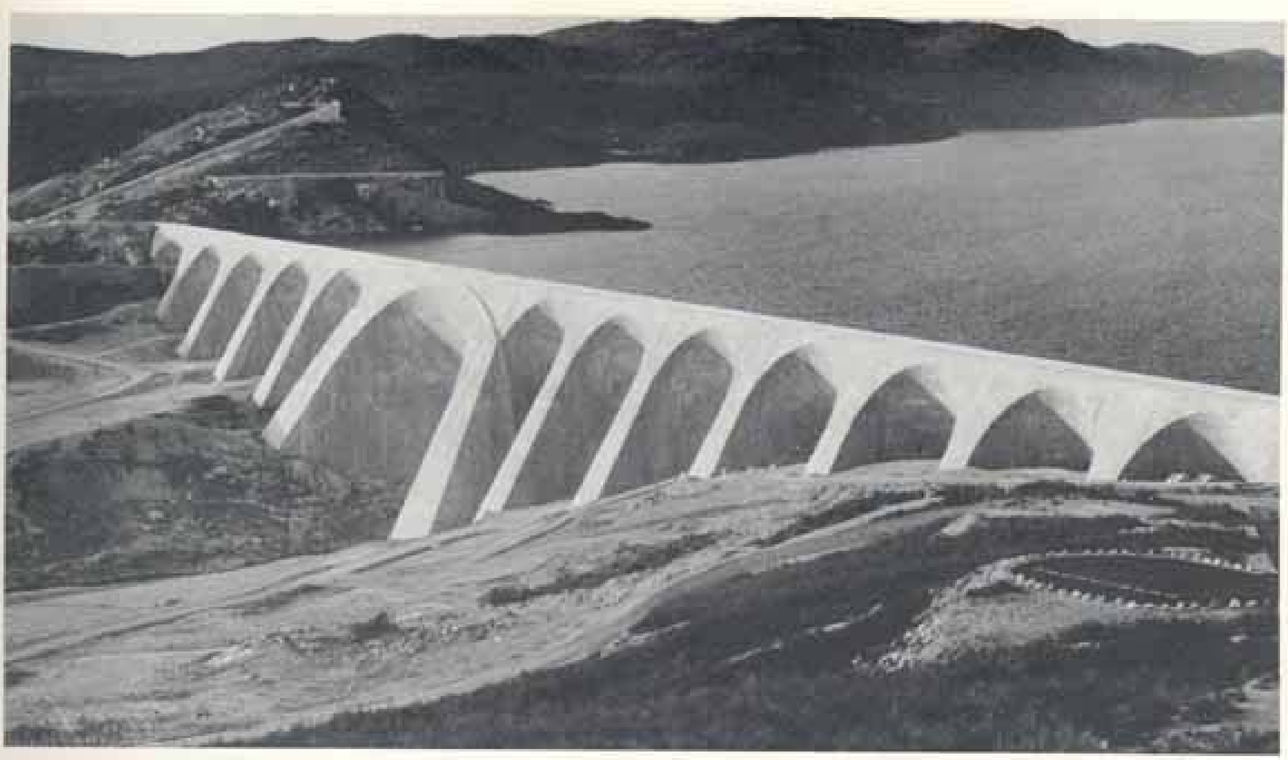


Figure 1-50.—Daniel Johnson (Manicouagan No. 5) Dam (Courtesy, Canadian National Committee, ICOLD). P-801-D-79337.

The dam has a nearly vertical core of glacial till and outer zones of compacted sand and gravel. Slope protection is dumped rock riprap. Total volume of the embankment is 32,100,000 cubic meters (42,000,000 cubic yards).

The increase in the number of dams since 1900 has been impressive. In the United States alone, the roster of major dams - more than 15 meters (49 feet) high, or between 10 and 15 meters (33 and 49 feet) and impounding more than 100 000 cubic meters (81 acre-feet) - grew from 116 in 1900 to 2635 in 1962. Around the globe, very high dams kept up with this rapid pace. Up to 1939, only 11 dams more than 100 meters (328 feet) high were completed - 5 in western Europe and 6 in the United States. By 1960, there were 88 such structures in operation throughout the world, and 65 more were built in just the next 5 years. New records have been set in quick succession. Outstanding height precedents for concrete structures have been achieved since mid-century by the Mauvoisin Dam **(fig. 1-51)** (1957) in Switzerland, 237 meters (777 feet); the Vaiont Dam **(fig. 1-51)** (1960) in Italy, 265 meters (869 feet); and the Grande Dixence Dam **(fig. 1-52)** (1962) 285 meters (935 feet)and Contra Dam **(figs. 1-53 and 1-54)** 220 meters (722 feet) (1965) in Switzerland.

On the Vaksh River in the Soviet Union, the construction of the Nurek Project, with a 317 -meter (1040 feet) high embankment dam **(fig. 1-55),** is nearly complete. The total volume of embankment amounts to about 56,000,000 cubic meters (73,000,000 cubic yards).

The Soviets rate their Rogun (Raguni Dam) **(fig. 1-56)** as the highest in the world, with a height of 330 meters (1082 feet); crest length of 680 meters (2231 feet); downstream slope of 2 to 1; upstream slope of 2.4 to 1; and a volume of 71 500,000 cubic meters (93,500,000 cubic yards).

Another large Soviet dam is the concrete arch dam of the Inguri Project. As reported in 1979 publications, the Inguri Dam **(fig. 1-57)** is located 7 kilometers (4.3 miles) from the Dzhvari Village in a narrow gorge of the Inguri River. The arch dam has a crest 640 meters (2100 feet) long, not counting the thrust blocks at each end. The dam has a projected maximum height of 271.5 meters (891 feet). The dam thickness is 10 meters (32.8 feet) at the crest elevation and 52 meters (170.6 feet) at an elevation 50 meters (164 feet) above its base where it rests on a concrete block which serves to plug the canyon. The dam is an arch of the double curvature type. The estimated volume of concrete in the dam is 3 880,000 cubic meters (5,070,000 cubic yards).

The records for volume of dam are also being surpassed. The great mass of Fort Peck Dam is now overshadowed by the Tarbela Dam on the Indus River in Pakistan, with 142,000,000 cubic meters (186,000,000 cubic yards) of earth and rock.

Since the distant beginnings of human history, the engineering of dams has evolved from primitive trial-and-error ventures to increasingly sophisticated analytical approaches. Early dam building was an uncertain art resting on cumulative experience. As the centuries unfolded, the art was gradually merged with science. Mathematics and the mechanics of materials have become increasingly effective in development of safer designs. Theoretical analysis combined with the practical judgment of the experienced engineer will provide the best insurance as the search for water moves to new horizons.

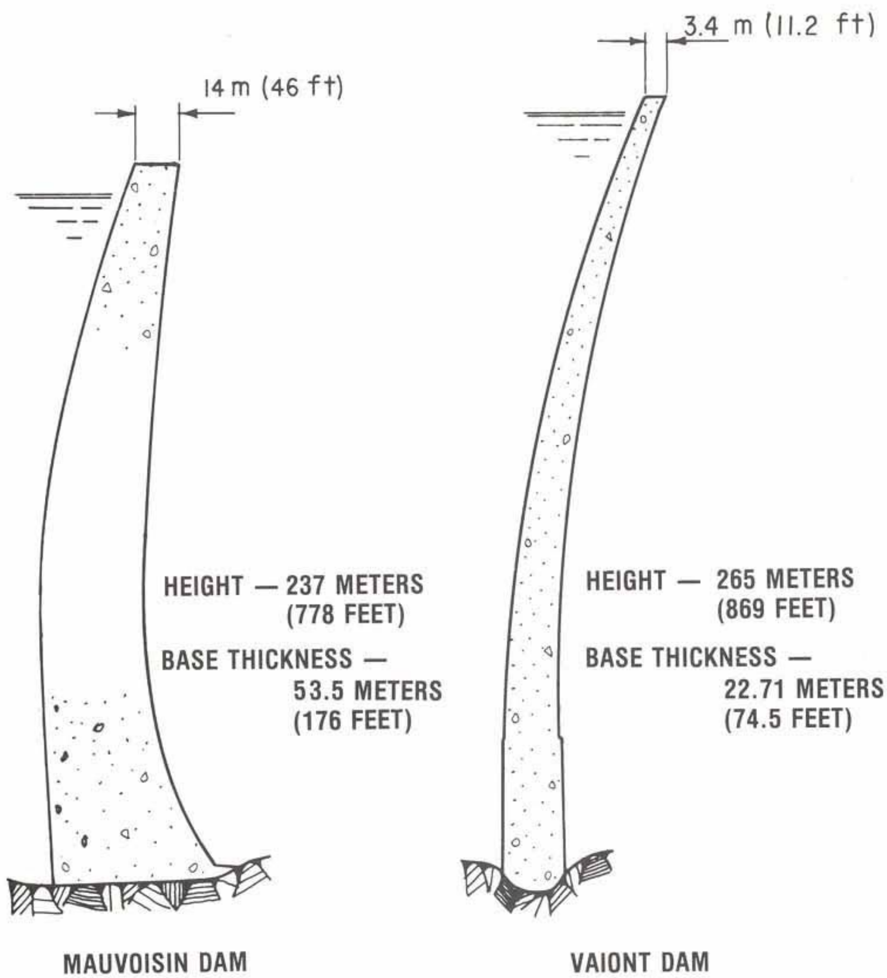


Figure 1-51.—Mauvoisin and Vaiont Dams, cross sections. P-801-D-79338.

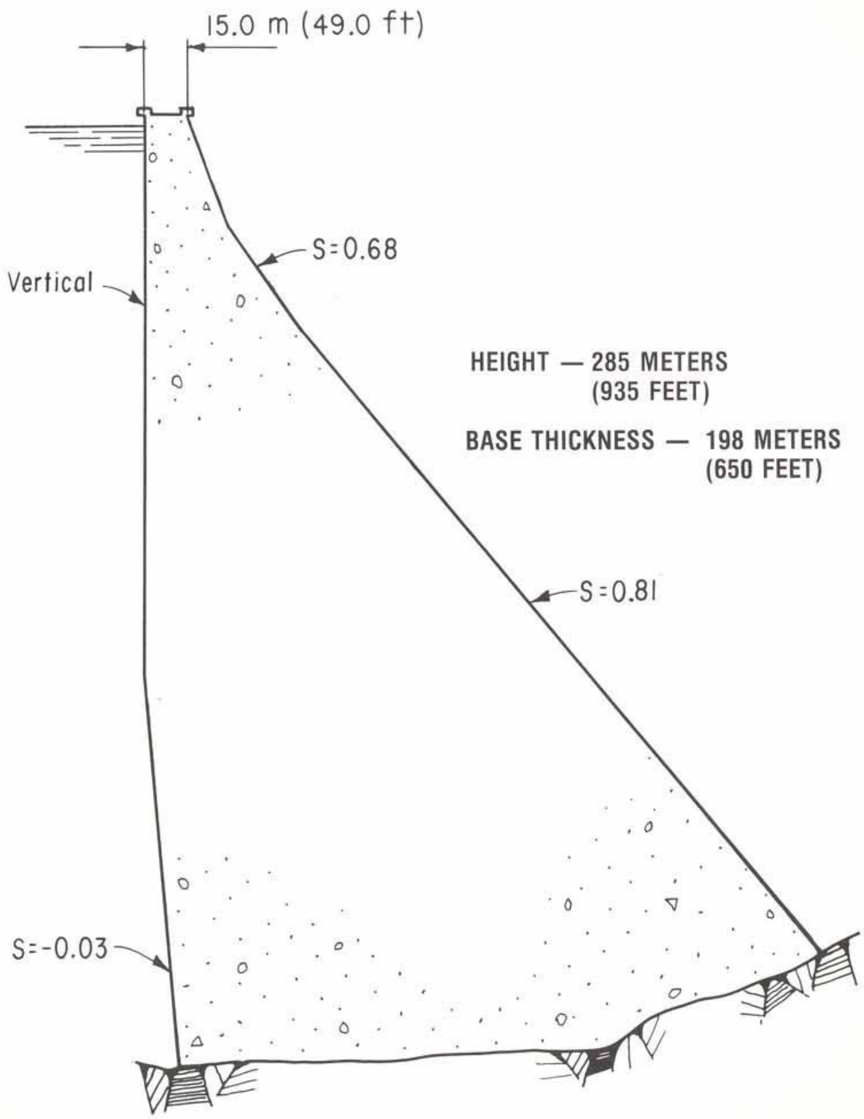


Figure 1-52.—Grande Dixence Dam, cross section. P-801-D-79339.

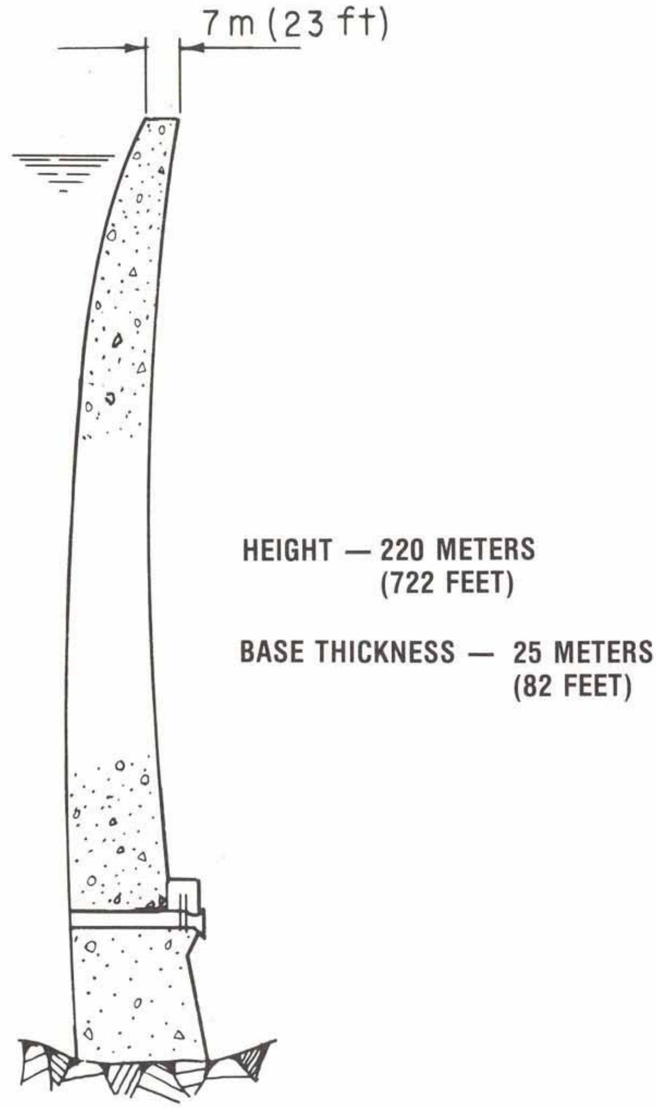


Figure 1-53.—Contra Dam, cross section. P-801-D-79340.

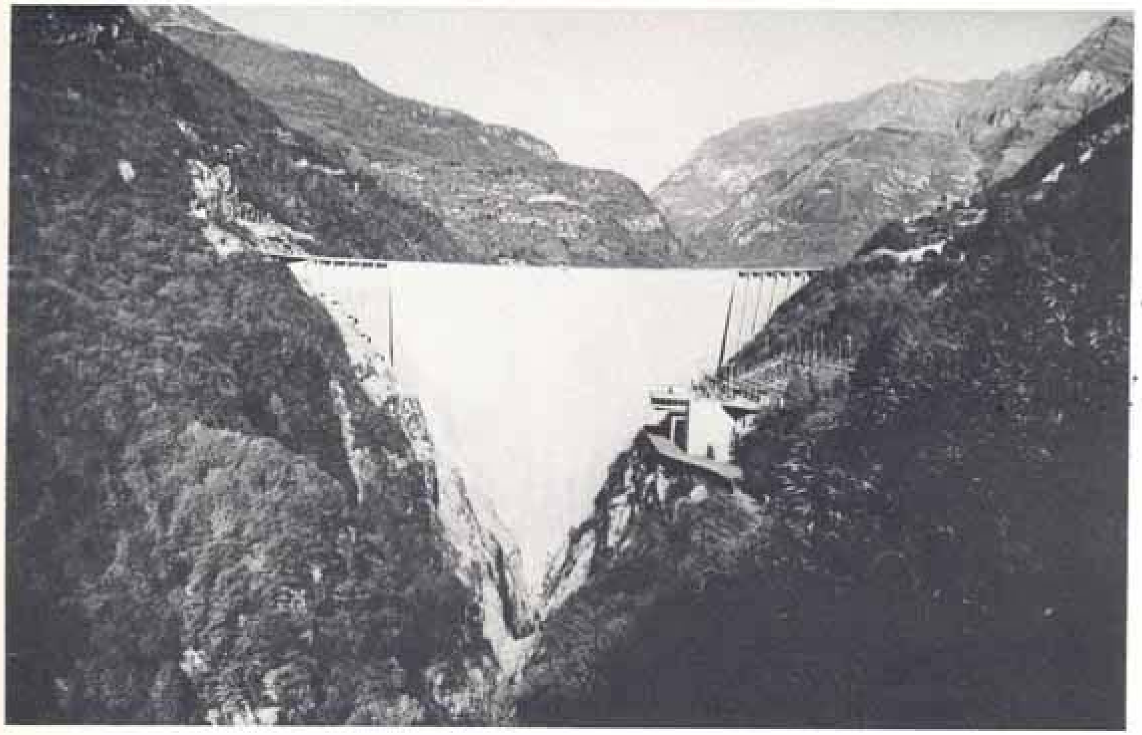


Figure 1-54.—Contra Dam (Courtesy, Comité National Suisse des Grands Barrages, ICOLD). P-801-D-79341.

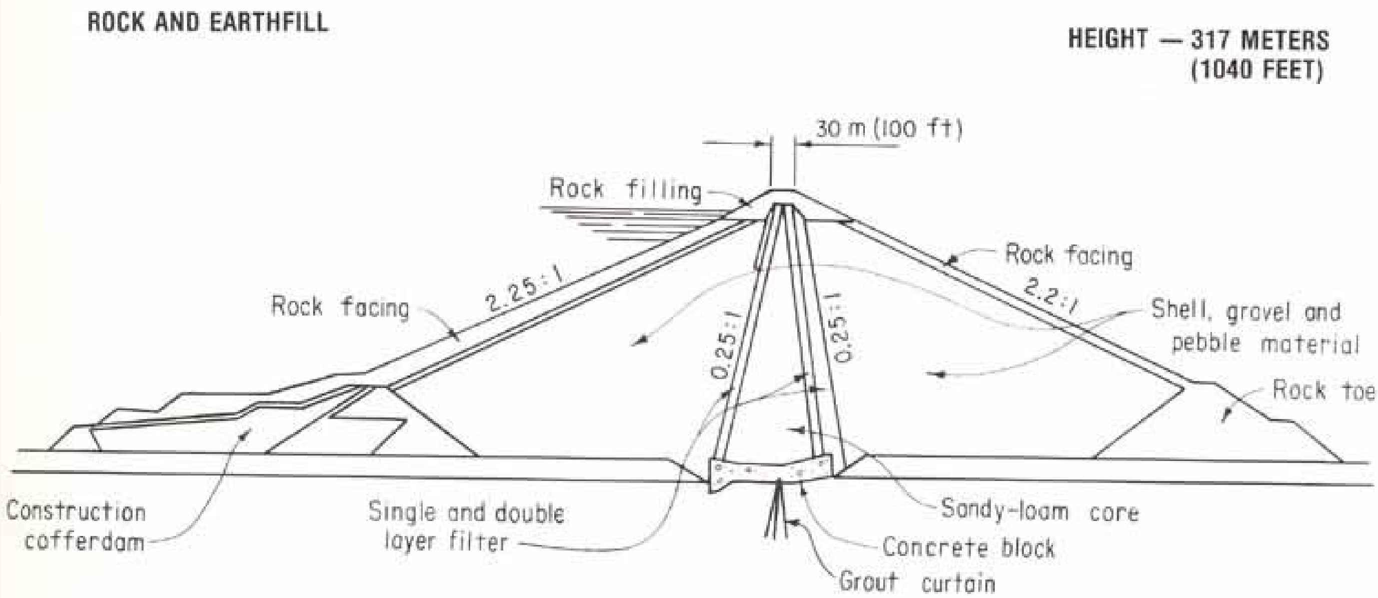


Figure 1-55.—Nurek Dam, cross section. P-801-D-79342.

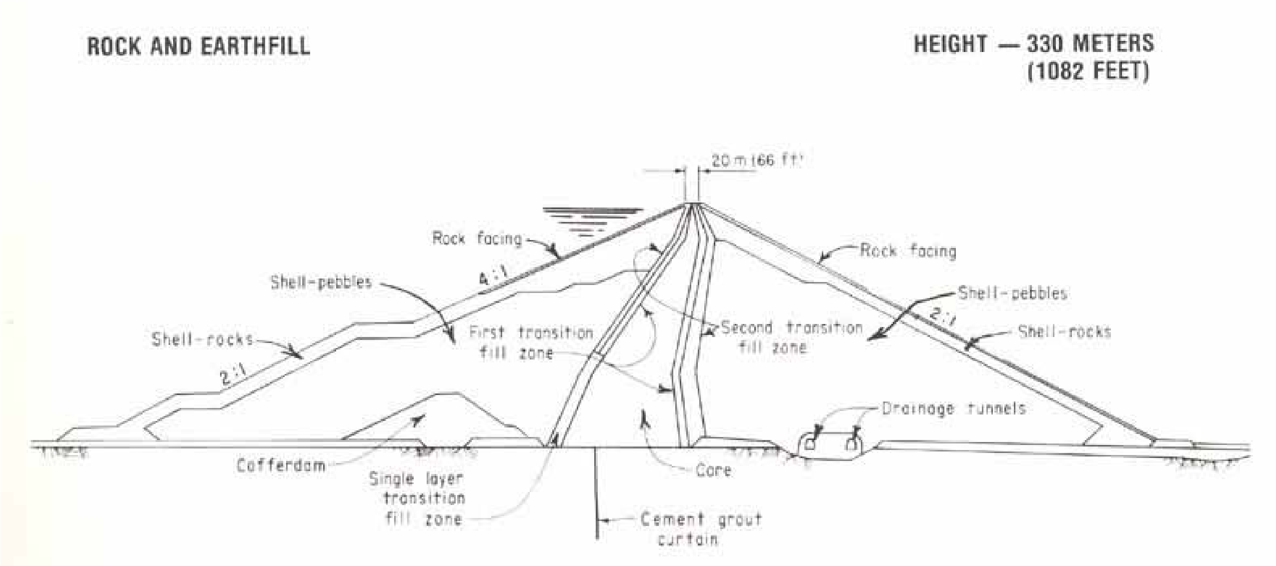


Figure 1-56.—Rogun (Raguni) Dam, cross section. P-801-D-79343.

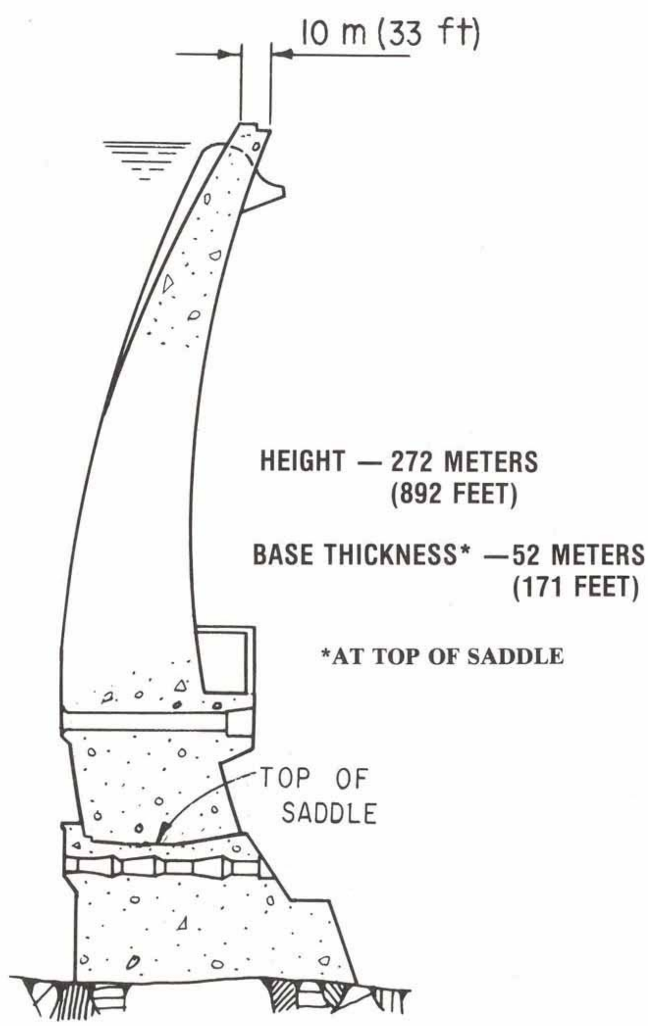


Figure 1-57.—Inguri Dam, cross section. P-801-D-79344.

A list of the highest dams in the world is shown in **table 1-1**.

Table 1-1.-*Highest dams in the world**

Name of Dam	Country	Type	Height Meters	Height Feet	Completed
Rogun (Raguni)	USSR	Earth	330	1082	U.C. (1985)
Nurek	USSR	Earth	317	1040	U.C. (1985)
Grand Dixence	Switzerland	Gravity	285	935	1962
Inguri	USSR	Arch	272	892	U.C. (1985)
Chicoasen	Mexico	Rockfill	264	866	U.C. (1980)
Vaiont	Italy	Arch	262	860	1961
Mica	Canada	Earth	242	794	1973
Sayan -Shushen	USSR	Arch	242	794	U.C. (1980)
Mauvoisin	Switzerland	Arch	237	777	1957
Chivor	Colombia	Rockfill	237	776	1975
Oroville	USA (Calif.)	Earth	236	770	1968
Chirkey	USSR	Arch	233	758	1975
Bhakra (Gobind Sagar)	India	Gravity	226	741	1963
EI Cajon	Honduras	Arch	226	741	U.C. (1984)
Hoover	USA (Ariz.-Nev.)	Arch-Gravity	221	726	1936
Contra	Switzerland	Arch	220	722	1965
Mratinje	Yugoslavia	Arch	220	722	1976
Dworshak	USA (Idaho)	Gravity	219	717	1972
Glen Canyon	USA (Ariz.)	Arch	216	710	1964
Toktogul	USSR	Arch	215	705	1968
Daniel Johnson (Manicouagan No.5)	Canada	Multiple Arch	214	702	1968
Auburn	USA (Calif.)	**	210	685	U.C.
Luzzone	Switzerland	Arch	208	682	1963
Keban	Turkey	Rockfill-Gravity	207	679	1974
Mohamad Reza Shah Pahlavi	Iran	Arch	203	666	1963
Almendra	Spain	Arch	202	662	1970
Reza Shah Kabir	Iran	Arch	200	656	1973
Tachien	Taiwan	Arch	200	656	1973
K'olnbrein	Austria	Arch	198	650	1978
New Bullards Bar	USA (Calif.)	Arch	194	637	1970
New Melones	USA (Calif.)	Rockfill	191	625	1975
Swift	USA (Wash.)	Rockfill	186	610	1958
Kurogegawa No.4	Japan	Arch	186	610	1964
Mossyrock	USA (Wash.)	Arch	185	607	1968
Shasta	USA (Calif.)	Arch-Gravity	183	602	1945
Bennett, W.A.G.	Canada	Earth	183	600	1967

* As reported in Water Power & Construction, November 1979 or The International Commission on Large Dams "World Register of Dams."
**Originally designed as an arch, but currently under reevaluation for seismic loading. Rockfill and curved concrete gravity dam alternatives are being considered.